Chapter III. Gold Deposits

Introduction

The primary gold content of igneous bodies of rock is low (0.004 ppm), and bodies with economic concentrations of the element are unknown except where later shearing and fracturing has taken place permitting the development of veins, stockworks and replacement lodes. In carbonatites gold is found only in traces, but some of these bodies contain higher than normal amounts of silver. My analyses of the various rocks in carbonatite complexes show gold to be generally present in the range 0.005 ppm; the silver contents cluster around 3 ppm. Most of the gold is in pyrite, which may contain up to 0.075 ppm Au. Some pegmatites contain enrichments of gold, but few of these bodies are economic sources of the element. Certain skarn deposits contain economic concentrations of gold, and some have been mined solely as auriferous deposits; from others considerable amounts of gold are also won as a byproduct of copper, lead or zinc mining and smelting.

In hypogene veins, lodes, stockworks, mantos and other types of similar deposits, gold is frequently strongly enriched, and these deposits are one of the main sources of gold production in the world. It is of interest to note, however, that veins greatly enriched in silver, especially the Ni-Co arsenide–native silver type are notably low in gold. Analyses by the writer of such veins from Cobalt and elsewhere in Canada show gold to be present in amounts clustering around 0.05 ppm in the ores. Disseminated gold deposits, many with a bedded (stratabound) aspect, developed in limestones, limy shales and schists, iron formations and other types of sedimentary rocks have been exploited in recent years.

The most productive gold deposits are those found in quartz-pebble conglomerates. Some of these deposits also yield uranium, rare-earths and small amounts of platinum metals.

Gold has been won extensively through the centuries from ancient and recent placers, both eluvial and alluvial. Unusual types of placers developed in karst terranes produce gold in some countries.

Finally, gold is won as a byproduct of many other types of metalliferous deposits including massive and disseminated Ni-Cu sulphide ores associated with basic rocks, massive Pb-Zn-Cu sulphide ores in volcanic and sedimentary terranes, various types of polymetallic deposits and the so-called porphyry Cu-Mo deposits.

This chapter deals with the classification of gold deposits, an outline of the metallogenic epochs of gold mineralization, the elements associated with gold in its deposits, the common minerals associated with gold in its deposits, a discussion of the Au/Ag ratio in deposits, an outline of wall-rock alteration processes in epigenetic gold deposits, descriptions of typical gold deposits including placers and ends with a section on the origin of epigenetic gold deposits and the controversial auriferous quartz-pebble conglomerates.

Classification of gold deposits

The following summary of gold deposits differs somewhat from the commonly accepted classifications given in most textbooks on economic geology. This departure may or may not be justified, but it is the writer's opinion that a classification based on the geological and geochemical setting of gold deposits is much more valuable than any based on their origin be it magmatic, hydrothermal, sedimentary or otherwise. It seems best to state objectively in what types of rocks and structural settings the deposits occur. With this clearly set down and a knowledge of the geochemistry of the deposits, it may be possible to discern their origin and, more importantly, to predict the environment where one may prospect for similar deposits. In the last 50 years many investigators have advocated a magmatic hydrothermal origin for all gold deposits – an extreme view that is fundamentally erroneous, because it fails to consider many of the geochemical features of gold, especially the behaviour of the element in the cycle of weathering and the part played by metamorphic processes in concentrating the element.

The classification suggested by the writer considers gold deposits under nine main categories, as follows:

1. Auriferous porphyry dykes, sills and stocks; auriferous coarse-grained granitic bodies, aplites and pegmatites.
2. Auriferous skarn-type deposits.
3. Gold-silver and silver-gold veins, stockworks, lodes, mineralized pipes and irregular silicified bodies in fractures, faults, shear zones, sheeted zones and breccia zones essentially in volcanic terranes.
4. Auriferous veins, lodes, sheeted zones and saddle reefs in faults, fractures, bedding-plane discontinuities and shears, drag folds, crushed zones and openings on anticlines essentially in sedimentary terranes; also replacement tabular and irregular bodies developed near faults and fractures in chemically favourable beds.
5. Gold-silver and silver-gold veins, lodes, stockworks, silicified zones, etc. in a complex geological environment, comprising sediments, volcanics and various igneous intrusive and granitized rocks.
6. Disseminated and stockwork gold-silver deposits in igneous, intrusive, volcanic and sedimentary rocks. (a) Disseminated and stockwork gold-silver deposits in various igneous intrusive bodies. (b) Disseminated gold-silver occurrences in volcanic flows and associated volcaniclastic rocks. (c) Disseminated gold-silver deposits in volcaniclastic and sedimentary beds: Deposits in tuffaceous rocks and iron-formations and deposits in chemically favourable sedimentary beds.

7. Gold deposits in quartz-pebble conglomerates and quartzites.

8. Placers. (a) Eluvial, including those developed in karst terranes. (b) Alluvial. (c) Fossil eluvial and alluvial.

9. Miscellaneous sources of gold.

> *L'or est de tous les âges*
> *—Proust, 1920*

Metallogenetic epochs and provinces of gold mineralization

Lindgren (1933) defines a 'metallogenetic' epoch as the time interval favourable for the deposition of certain useful substances and a 'metallogenetic' province as an area in which mineralization has been active at one or more periods.

The literature of economic geology is replete with discussions of the metallogenic epochs of gold mineralization, and numerous world maps have been published outlining metallogenic gold provinces. The auriferous metallogenic epochs are summarized in Table 28 and the geological distribution of gold deposits are generalized in Figures 3, 5, 6 and 7. It should be emphasized that both the table and the figures are no more than general guides.

The following books, papers and maps have greatly assisted the writer in compiling the data on the metallogenesis of gold: Curle (1905), Maclaren (1908), De Launay (1913), Lindgren (1909, 1917, 1933), Redmayne (1922), Miller and Singewald (1919), Dunn (1929), International Geological Congress (1930), Kittl (1931–1932), Finch (1933), Bruce (1933), Chibber (1934), Emmons (1937), Cooke (1946), Juan (1946), Hills (1947), Gmelin (1950–1954), Bateman (1950), Bilibin (1947, 1950, 1955), Ho (1953), Freidensburg (1953), Edwards (1953), Turneaure (1955), Jenks (1956), Brinck (1956), Smirnov (1959), Burnham (1959), Petrovskaya (1960), Radkevich (1961), Bishopp (1962), Routhier (1963), Roy (1963), Ch'ang ta (1963), Rankama (1963–1970), Pelletier (1964), Laffitte and Rouveyrol (1964), McAndrew (1965), McLeod (1965), De Kun (1965), Campbell (1965), Sher (1966, 1972), Musylev (1966), Ogura (1967, 1969), Il'jin (1968, 1974), Rozhkov (1968*a,b*), Laffitte (1968–1970), Ridge (1968, 1972), Ramovic (1968), Koschmann and Bergendahl (1968), King (1969), Ianovici *et al.* (1969), Gümüs (1970), Petersen (1970), Folinsbee (1971), Kim (1971), Guild (1972), Magakian (1972), Galkiewicz (1972), Shilo (1971, 1972), Warren (1972), Goossens (1972), Abreu (1973), Hughes (1973), Tsypukov and Lombo (1973), Takashima and Igarashi (1973), Fisher (1973), Cordani *et al.* (1973), Konstantinov (1974), Itsikson (1974), Choubert (1974), Smirnov (1974), Williams (1974), Anhaeusser (1976*a,b*) and Knight (1975); also the various geological maps and reports published by geological societies and surveys throughout the world.

The geological history of the earth has been marked by a number of epochs of epigenetic gold mineralization, the greatest of which took place in Precambrian time. Younger epochs occurred in Paleozoic, Mesozoic and Cenozoic times. Gold placers are known in sedimentary rocks of practically all ages, particularly in those of Tertiary and Quaternary age. If it is accepted that the Witwatersrand deposits are placers, or modified placers, the greatest epoch of formation of gold placers occurred in Precambrian time.

Precambrian

Gold deposition took place extensively during Precambrian time (Fig. 3), the typical auriferous deposits formed being mainly gold-quartz veins and silicified zones and modified placer quartz-pebble conglomerates. Gold was also deposited during this time in skarn deposits, polymetallic lodes, massive sulphide bodies, disseminated and massive Ni-Cu sulphide deposits, and other types of metalliferous lodes. Most of the typical auriferous quartz deposits occur in volcanic rocks and their associated sediments, mainly greywacke and slate; the modified placers are in pyritiferous or hematitic quartz-pebble conglomerates and associated quartzites.

In North America most of the Precambrian auriferous deposits occur in the Canadian Shield and in the Black Hills of South Dakota. Other deposits, probably of Precambrian age, are known in the Appalachian fold belt of the United States and Canada, and in folded and metamorphosed rocks in Wyoming, New Mexico and Arizona. In all of these widely separated areas the principal deposits belong to the gold-quartz and disseminated types, developed mainly in volcanic and sedimentary terranes. Precambrian skarn-type deposits are of minor importance as gold producers. Considerable quantites of gold are won from a variety of polymetallic lodes, massive Cu-Zn sulphide bodies, Ni-Cu ores associated with basic rocks and other types of metalliferous bodies. The known pyritiferous quartz-pebble conglomerates in the Precambrian (Lower Proterozoic; Aphebian) of North America carry only minor amounts of gold and silver. Because of extensive glaciation only small and economically insignificant gold placers occur in the Canadian Shield; in the United States placers developed from Precambrian gold deposits have been of some importance. More details on the metallogenic epochs of gold mineralization in the Canadian Shield are discussed below.

The Early, Middle and Late Precambrian formations of South America, occurring mainly in the Brazilian and Guyanian shields, contain numerous gold deposits principally in the Brazilian states of Bahia and Minas Geraes, in Uruguay, and in the Guyanas and Venezuela. Most of the primary auriferous deposits are of the gold-quartz type or of the pyrite impregnation types as in Surinam (Brinck, 1956) and Guyana (Fernandes, 1961). In Venezuela the auriferous deposits are of three types (Pasquali and Bisque, 1975) – massive quartz veins with native gold; quartz veins containing abundant pyrite; and zones of gold-bearing pyrite in sheared lavas, without quartz. There are also auriferous quartz-pebble conglomerates in the Serra de Jacobina in Brazil. In the Cordillera of South America numerous areas are underlain by undifferentiated Precambrian rocks that are apparently difficult to separate from those of Paleozoic age. A number of gold deposits occur in these rocks, but their age is uncertain. Most investigators consider them to be Paleozoic or younger, and hence they are discussed in the sections that follow. Placers developed from the Precambrian deposits are or were important in the Guyanas, Venezuela and Brazil.

Precambrian gold deposits, ranging in age from Archean to Proterozoic, occur in many parts of Africa. In fact, the oldest of all gold mines, those in Egypt (Nubia), seem to have been worked more than 4000 years ago. From Egypt and Sudan, east of the Nile, great belts of Precambrian rocks

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Table 28. Characteristics of the principal auriferous metallogenic epochs of the world

Era	Precambrian (3000–570)*	Paleozoic (570–225)*	Mesozoic (225–65)*	Cenozoic (65–0)*
Age of host rocks	Gold-quartz deposits mainly in Archean rocks (>2500 m.y.); extensive deposits in Proterozoic quartz-pebble conglomerates; some large gold-quartz and varied stockwork deposits in Proterozoic rocks	Mainly Paleozoic; some deposits in Precambrian or both Paleozoic and Precambrian rocks	Mainly Mesozoic but also Paleozoic and Precambrian	Mainly Tertiary but also all older rocks
Principal types of host rocks	Gold-quartz deposits mainly in meta-volcanics, iron – formation and meta-sediments of greywacke-slate type; also in associated quartz-feldspar porphyries and other granitic rocks. Largest deposits in quartz-pebble conglomerates and associated quartzites (modified placers)	Gold-quartz and skarn-type deposits mainly in metasediments, especially in greywacke-slate sequences; similar deposits in meta-volcanics, in porphyries and in granitic rocks	Gold-quartz and skarn-type deposits in meta-sediments and meta-volcanics	Andesites, dacites, tuffs, rhyolites and a great variety of meta-volcanic and meta-sedimentary rocks
Principal types of deposits	Modified placer (?) deposits in quartz-pebble conglomerates; gold-quartz veins, lenses, saddles, silicified zones, etc.; skarn types; auriferous polymetallic veins, lodes and massive sulphide bodies	Gold-quartz veins, lodes, lenses, silicified zones; saddle reefs and bedding-plane veins are characteristic in many areas. Skarn and hornfels types. Auriferous polymetallic veins, lodes and massive sulphide bodies	Gold-quartz veins, lodes, lenses, silicified zones; skarn-type deposits; auriferous polymetallic veins, lodes and massive sulphide bodies	Gold-quartz veins, lodes, lenses and silicified zones; auriferous polymetallic veins, lodes and massive sulphide bodies
Principal gangue minerals	Quartz-pebble conglomerates – pyrite, quartz, hematite, sericite. Gold-quartz type – quartz, pyrite, arsenopyrite, pyrrhotite, carbonates	Quartz, pyrite, arsenopyrite and carbonates	Quartz, pyrite, arsenopyrite and carbonates	Quartz, pyrite, arsenopyrite carbonates, adularia, alunite, fluorite, barite; rhodochrosite and rhodonite are characteristic
Principal metallic minerals	Quartz-pebble conglomerates – pyrite, hematite. Gold-quartz type – pyrite, pyrrhotite, arsenopyrite, galena, sphalerite, chalcopyrite, stibnite and sulphosalts	Pyrite, arsenopyrite, pyrrhotite, chalcopyrite, galena, sphalerite, stibnite and sulphosalts	Pyrite, arsenopyrite, pyrrhotite, chalcopyrite, galena, sphalerite, stibnite and sulphosalts	Pyrite, arsenopyrite, chalcopyrite, galena, sphalerite, argentite, sulphosalts, stibnite and silver selenides
Nature of the gold	Quartz-pebble conglomerates – free gold, average size 80 microns. Gold-quartz type – free gold and as a lattice or submicroscopic constituent of pyrite, arsenopyrite, sulphosalts, etc; in tellurides	Generally free; in some deposits much of the gold is present as a lattice or submicroscopic constituent of pyrite, arsenopyrite, sulphosalts, etc; in tellurides	Generally free; in some deposits much of the gold is present as a lattice or submicroscopic constituent of pyrite, arsenopyrite, sulphosalts, etc; in tellurides	Generally free; in some deposits much of the gold is present as a lattice constituent or submicroscope constituent of pyrite and various sulphosalts; in tellurides
Characteristic associated elements†	K, Na, Cu, Ag, Zn, Cd, B, Th, U, rare earths, SiO_2, Pb, As, Sb, Bi, Te, (Se), Mo, W, Cr, Mn, Fe, (Co), (Ni), (Pt metals). U, Th, and rare earths are characteristic of quartz-pebble conglomerates	K, Na, (Sr), (Ba), (Mo), W, (Co), (Ni), Cu, Ag, Zn, Cd, (Hg), B, (Sn), Pb, As, Sb, Bi, (Se), Te, (F)	K, Na, (Sr), (Ba), (Mo), W, (Co), (Ni), Cu, Ag, Zn, Cd, (Hg), B, (Sn), Pb, As, Sb, Bi, (Se), (Te), (U), (F)	K, (Sr), Ba, (U), Mo, W, Mn, (Co), (Ni), Cu, Ag, Zn, Cd, Hg, (B), Tl, (Sn), Pb, As, Sb, Bi, Se, Te, F
Characteristic wall-rock alteration processes	Pyritization, arsenopyritization, carbonatization, sericitization, biotitization, tourmalinization, chloritization, silicification, albitization and development of skarn minerals. Development of pyrite, sericite, pyrophyllite in quartz-pebble conglomerates	Pyritization, arsenopyritization, carbonatization, sericitization, tourmalinization, chloritization, silicification, listvenitization, beresitization, albitization and development of skarn and hornfels	Pyritization, arsenopyritization, carbonatization, sericitization, tourmalinization, chloritization, silicification, albitization, listvenitization, beresitization, (alunitization), development of adularia; development of skarn and hornfels	Pyritization, carbonatization, sericitization, chloritization, silicification, alunitization; propylitization is widespread in most auriferous areas.

*Approximate duration of the geological eras (in millions of years).

†Excluding the common and nearly universal associates such as Si, Fe, S, etc.; elements in brackets are rare or localized.

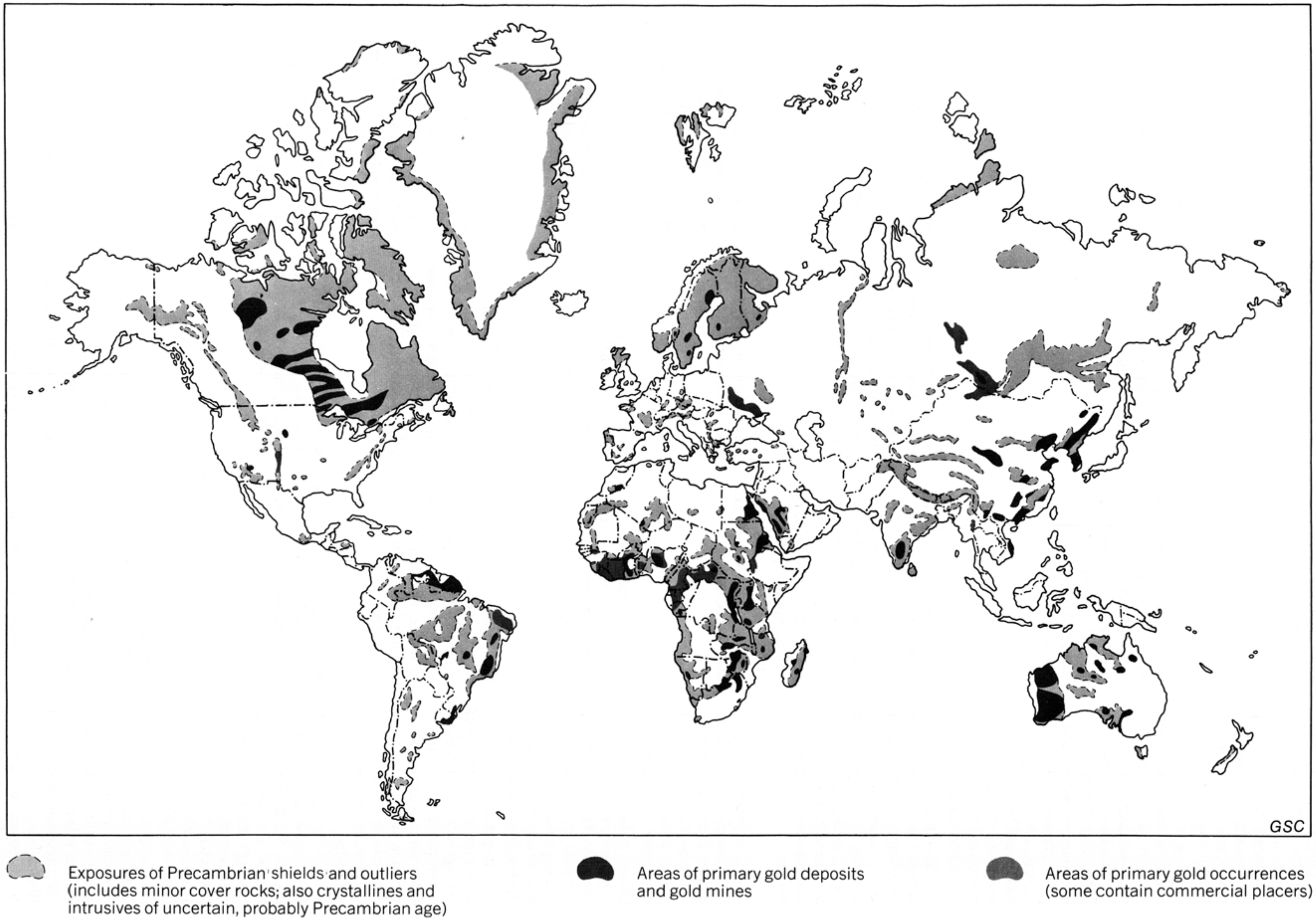

Figure 3. World distribution of primary gold deposits and occurrences of Precambrian age.

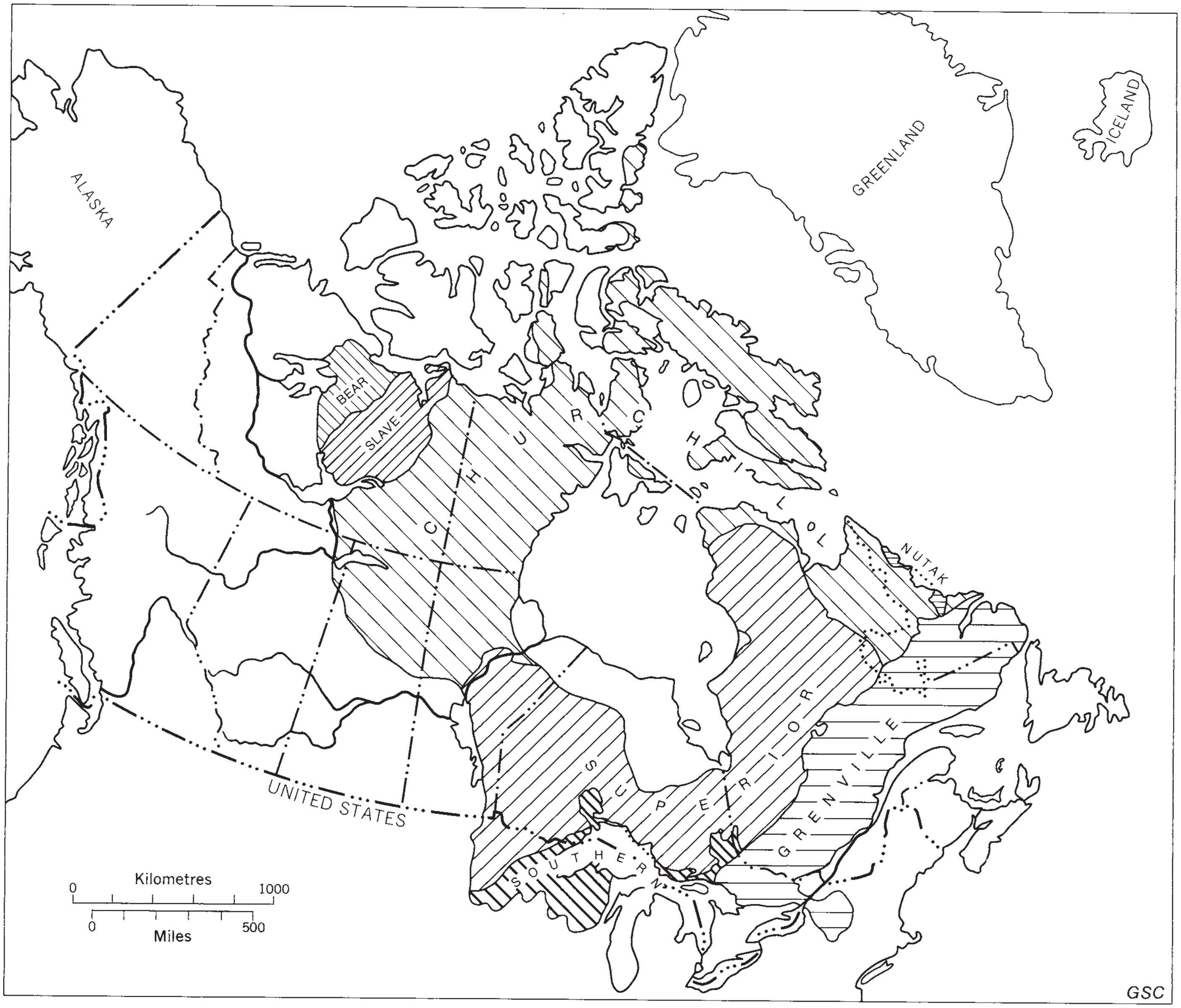

Figure 4. Canadian Shield showing the various structural provinces.

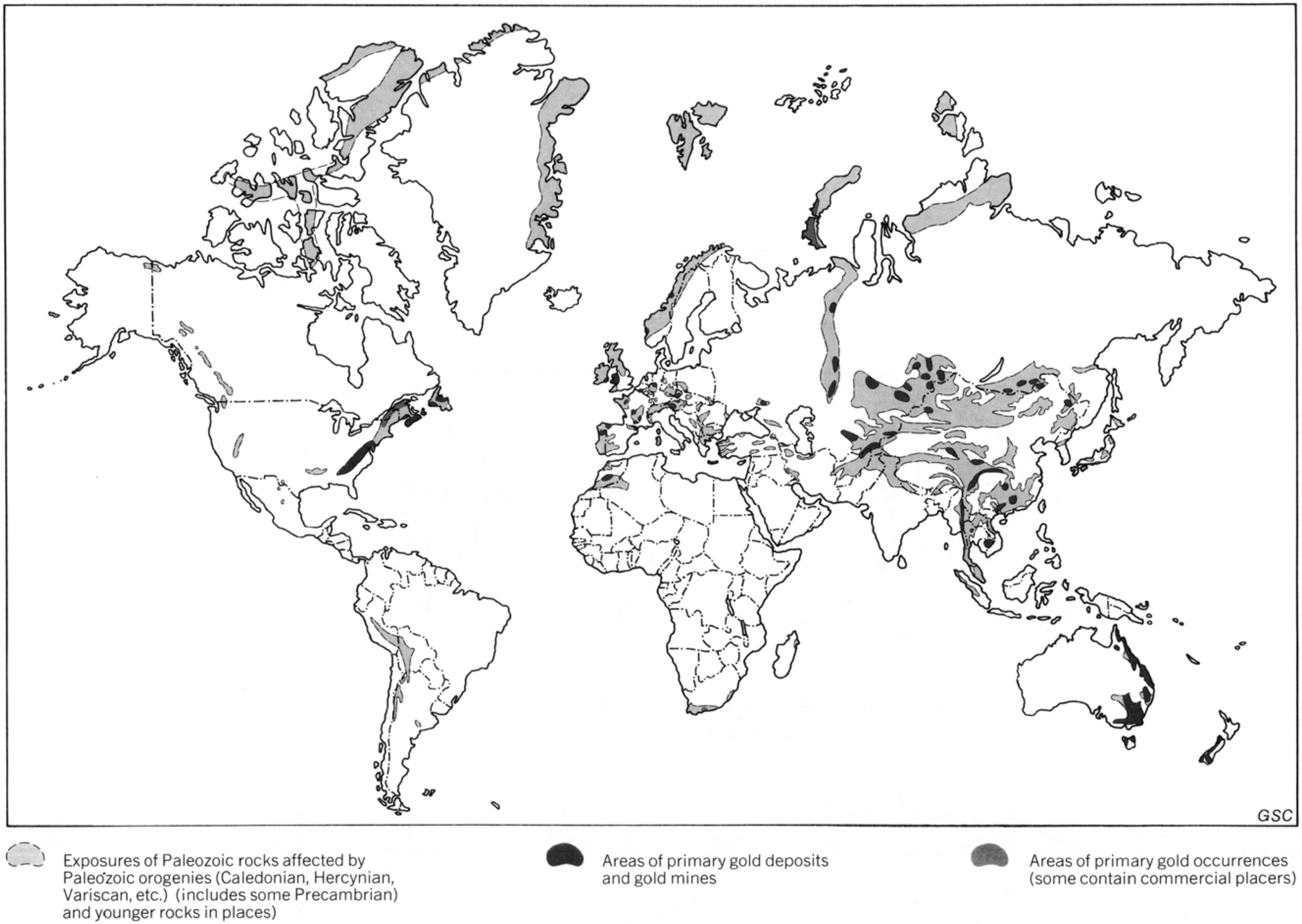

Figure 5. World distribution of primary gold deposits and occurrences of Paleozoic age.

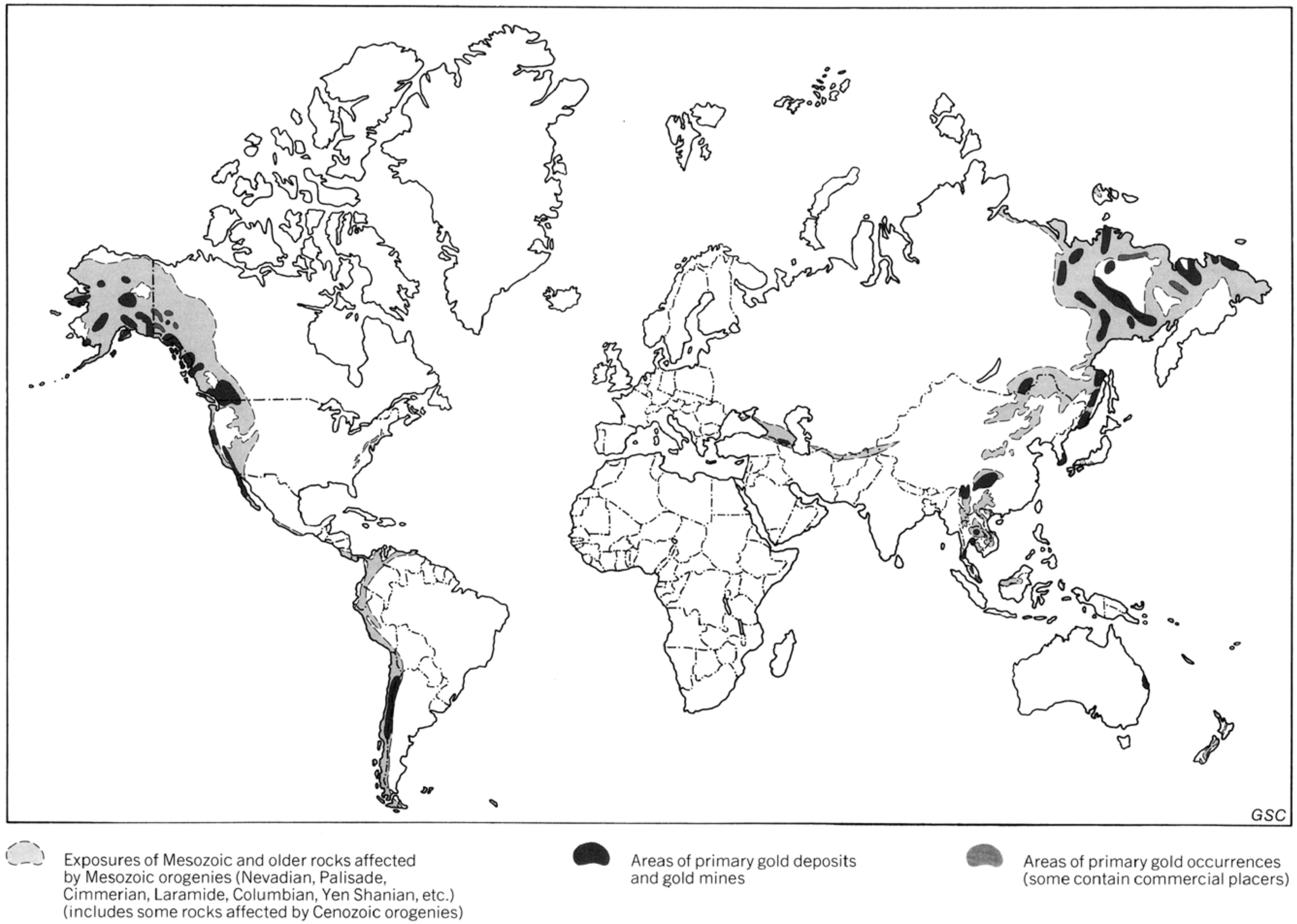

Figure 6. World distribution of primary gold deposits and occurrences of Mesozoic age.

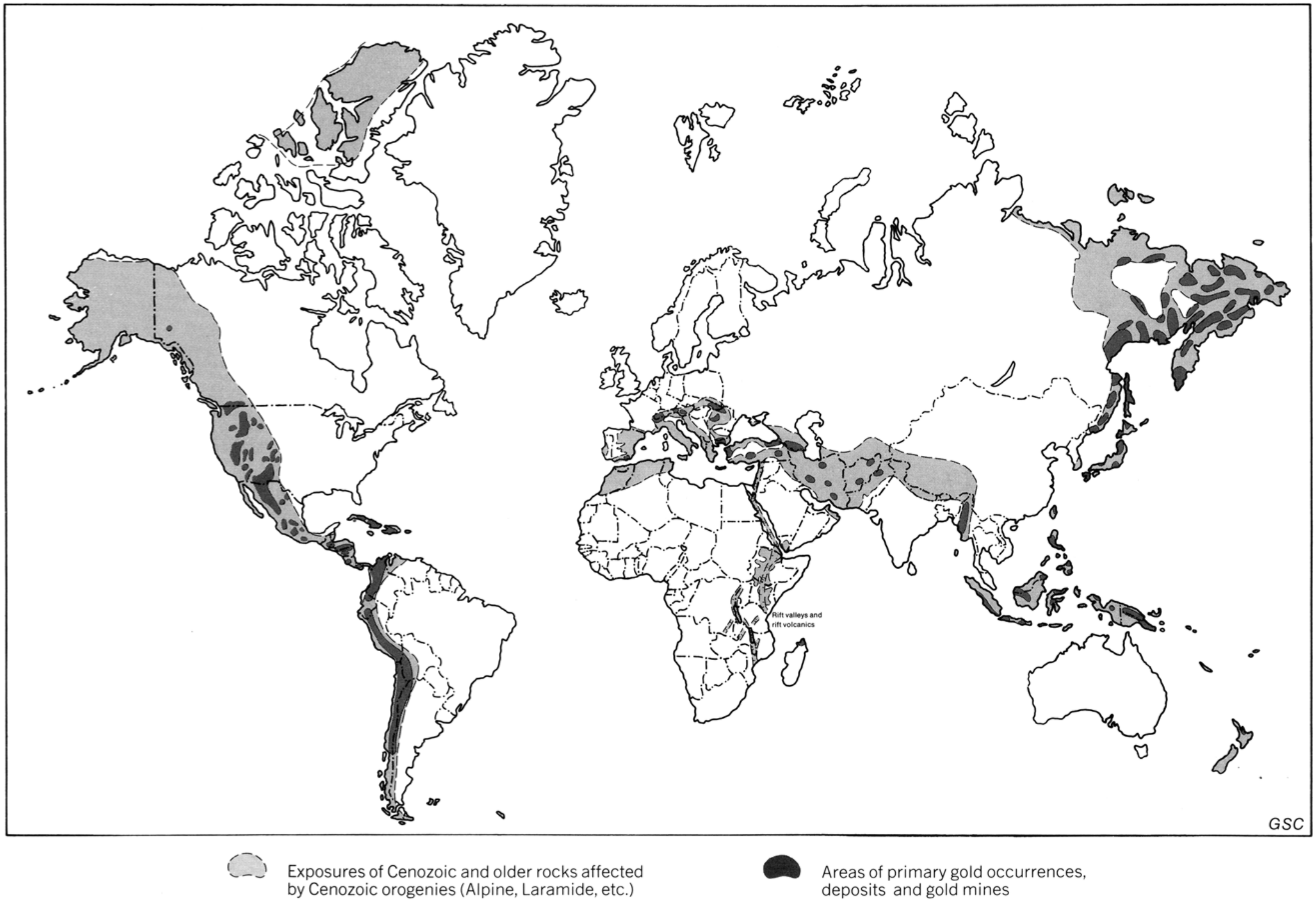

Figure 7. World distribution of primary gold deposits and occurrences of Cenozoic age (may include some deposits older than Tertiary).

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stretch longitudinally to the Cape Province of South Africa and transversely from the Gulf of Aden almost to the western extremity of the continent. Precambrian rocks also underlie most of the Malagasy Republic (Madagascar Island) and occur in a narrow belt adjoining the west coast of the African continent from the Gulf of Guinea southward. Throughout these rocks there are a vast number of deposits of the gold-quartz type in veins and silicified zones developed in volcanic, sedimentary and granitic terranes. Many of these are small, but a number of deposits have yielded large amounts of gold. Disseminated types in banded iron-formations and polymetallic lodes of Precambrian age also yield some gold. Of special interest, principally in South Africa, are the Precambrian pyritiferous quartz-pebble conglomerates (Witwatersrand system), which contain the world's largest known concentrations of gold. Similar types of deposits, but with hematite instead of pyrite in the matrix, occur in quartz-pebble conglomerate in Ghana (Tarkwa field). Placers, developed mainly from the Precambrian gold-quartz veins and lodes, are important in many countries in Africa, particularly in Mauritania, Guinea, Senegal, Mali, Sierra Leone, Liberia, Ivory Coast, Upper Volta, Ghana, Togo, Dahomey, Nigeria, Cameroun, Angola, Uganda, Zaire, Malawi, Mozambique, Ethiopia and Malagasy.

In Europe, Precambrian rocks are exposed mainly in the Baltic (Fennoscandian) Shield, which underlies much of Norway, most of Sweden, Finland and northwestern U.S.S.R. west of the White Sea. Similar Precambrian rocks occur in the core of the Urals and underlie the Orel-Kursk region and a belt in the Ukraine, extending from a point east of Rovno to the sea of Azov (Ukranian Shield). Other areas of Precambrian rocks occur in the Hebrides, in northern Scotland and Ireland and in scattered areas in Wales and England (Anglesey, Malvern Hills, Charnwood Forest); also in some of the massifs of western Europe, viz. in France (Armorican), in Czechoslovakia (Bohemian) and in central Germany (Schwarz-wald). The Precambrian of Europe, especially in the Baltic Shield, is marked by four cycles of sedimentation separated by periods of granitic formation. The most intense and widespread tectonic and metamorphic events occur in the third or Karelidic cycle that ended about 1800 million years ago. The youngest Precambrian rocks (Middle and Late Proterozoic) are relatively fresh and are referred to the Riphean in U.S.S.R; in Norway these rocks are Eocambrian. Few important gold deposits of Precambrian age occur in the Precambrian rocks of Europe, although representatives of the skarn and pyrite-arsenopyrite-gold-quartz types are known in the Baltic Shield and have yielded some gold principally in the Adelfors and Skelleftea districts of Sweden and the Tampere district of western Finland (Haveri Mine). There are also gold-bearing deposits in eastern Karelia, U.S.S.R. (Voitovich and Khenkina, 1971). There, the Voitsk and Shuezersk deposits are mainly veins and lodes in strike-slip fault zones cutting phyllites, quartzites and graphitic schists, intruded by post-middle Proterozoic gabbro, diabase, diorite porphyries, granite porphyries and granosyenites. The principal ore minerals are chalcopyrite, pyrite, bornite, scheelite, molybdenite, galena, native gold, native copper, malachite and azurite, the last three probably of supergene origin. In the Kola Peninsula the productive gold deposits are mainly quartz veins and quartz-sulphide lodes (Lobanov, *in* Petroskaya, 1974). Some of the deposits in the Bohemian massif have also been mined extensively at Jilové, Roudny and elsewhere. Most of these deposits were auriferous quartz veins, some with relatively large amounts of antimony (stibnite), which was also won as a byproduct. Although found mainly in Precambrian rocks (gneisses, schists, phyllites and greenstones), these deposits are of Hercynian age (Morávek, 1971). Most of the gold won from the Precambrian of Europe has come from ores mined principally for their copper, zinc and lead content. Examples of these deposits are the massive copper sulphide deposits of Falun and Boliden in Sweden. The latter contains massive concentrations of pyrite, chalcopyrite, pyrrhotite, arsenopyrite, boulangerite, jamesonite, and bismuth- and selenium-bearing minerals. Some of the ores averaged over 0.5 oz Au/ton and 1.5 oz Ag/ton. Because of extensive glaciation only small placers of relatively little economic value occur in the Precambrian terranes of Europe.

In Asia large areas are underlain by Precambrian rocks in the Arabian Peninsula, U.S.S.R. (Siberia), Mongolia, China, Korea and India. These rocks are generally subdivided into two great groups of Archean and Proterozoic age. The Precambrian rocks in Siberia and the Asian part of U.S.S.R. underlie part of the Pamirs; an area southeast of Kyzyl (Sangilen massif); areas west, northwest and northeast of Irkutsk (Baikalides); west of the Sea of Okhotsh (Aldan Shield); north of Vladivostok (Khanka massif); west of Birobidzhan (Bureya massif); southeast of Khatanga (Anbar Shield); part of the Cherskiy mountain range (Kolyma massif); and other scattered areas east to Bering Strait. A review of the Precambrian of U.S.S.R. is given by Salop (1964). In Mongolia, Precambrian rocks occur in the western part of the country and in scattered areas elsewhere. North Korea and parts of South Korea are underlain by Precambrian schists of sedimentary origin intruded by a variety of granitic rocks. In China, most of the Precambrian rocks occur in Manchuria and in a number of belts in the central, western and southern part of the country. Three great systems are differentiated: T'ai Shan (Archean?), Wu-t'ai and Sinian (Proterozoic?). The first consists of highly metamorphosed sedimentary and igneous rocks, mostly gneiss and schist, and the second comprises less metamorphosed sediments. The Sinian consists mainly of sediments, including arkosic clastics below grading up into thick cherty limestones. The Sinian also includes sedimentary iron ore, tillites and local lava flows. These are unmetamorphosed except where involved in much later mountain-forming disturbances and generally resemble the overlying Paleozoic formations. In India a great belt of Precambrian rocks underlies the central, eastern and southern part of the peninsula. Similar rocks underlie much of Sri Lanka (Ceylon). There are no definite Precambrian rocks in Japan, although certain groups of metamorphics (Hida series) may have a Precambrian component.

Numerous gold deposits occur in the Precambrian of Asia. Most belong to the gold-quartz type developed in ancient (Archean) volcanic and sedimentary terranes. Typical examples of these are the famous deposits of Mysore, India (Kolar and other fields) in metavolcanics and associated sediments. Numerous ancient gold mines were worked in metavolcanic and metasedimentary rocks in Saudi Arabia as far back as King Solomon's time. Most workings were in the oxidized zones of gold-quartz-pyrite veins and lodes in fissures and shear zones; one deposit, the Mahd Ad-Dahab, now works hypogene quartz-pyrite ores in rhyolite breccias (Kingdom of Saudi Arabia, 1965, 1969, 1970). According to some geologists these deposits are of Riphean age (Proterozoic) related to granitic bodies of the same age. In Korea gold-quartz veins are mined or were formerly mined at Unsan, Nurupi, Sak Ju, Sen Sen and elsewhere. Numerous gold deposits of Precambrian age are also known in China, but in recent years there has been little information available on their nature and exploitation. Judging from the older reports (Wong, 1919; Emmons, 1937; Juan, 1946) most of the deposits are gold-quartz veins, gold-bearing skarns and gold-quartz-sulphide lodes related to orogenic events at the end of the Algonkian (Proterozoic). The host rocks are mainly greenstones (amphibolites), schists and gneisses invaded by a variety of granitic rocks. Despite their considerable extent and similarity in rock types to shields in other countries containing large gold deposits, the shields and areas of Precambrian rocks in the Asiatic as well as those in the European part of U.S.S.R., including the Baltic, Ukranian, Aldan and Anabar shields apparently contain few commercial deposits of Precambrian age mined exclusively for gold (Rozhkov and Zhadnova, 1972; Borodaevskaya and Rozhkov 1974; Buryak *et al.,* 1974). There are, however, numerous gold occurrences in these various areas of Precambrian rocks, some apparently of Precambrian age (Buryak, 1967 *a,b,c*; Buryak *et al.,* 1974) and some of later age (Zakharov, 1971). The gold mineralization described by Buryak *et al.* (1974) in the Sayan-Baikal folded belt consists of three types: slightly auriferous polymetallic sulphide desposits, gold-quartz veins and impregnation sulphide deposits containing some gold. These deposits occur mainly in phyllites, shales, carbonate rocks and basic volcanic flows. The mineralization is older than the Early Proterozoic granitic rocks and hence may be of Archean age. According to Perelygina (1973) most of the gold deposits in the Aldan Shield, some of commercial grade, are associated with the rejuvenated parts of the shield marked by the Aldan volcano-plutonic complex of Late Mesozoic age. The deposits include gold-sulphide bodies and veins, oxidized gold-pyrite-quartz bodies (Kuranakh-type), auriferous silicified and limonitized zones, auriferous quartz veins and pyritized zones and auriferous zones characterized by potassic feldspar-pyrite-carbonate metasomatites. Much gold is won from a variety of polymetallic deposits in Precambrian Proterozoic rocks in U.S.S.R. (Smirnov, 1959). Similar polymetallic deposits in Precambrian rocks in China, Korea and other countries in Asia yield some gold. The age of these deposits is uncertain. So far as is known economic gold-bearing quartz-pebble conglomerates have not been found in the Precambrian of Asia, although a number of occurrences have been reported (*see* the section on fossil placers). Numerous large gold placers derived in part from lean deposits in Precambrian rocks are worked in the headwaters of the Lena River (Aldan Shield), in a number of rivers north of Manchuria and elsewhere in U.S.S.R. (*see* Fig. 87). Similar, but smaller gold placers derived from Precambrian deposits have been exploited in Mongolia, China, Korea, India and other countries in Asia.

The Precambrian of Australasia is concentrated principally in the great shield area of Western Australia and parts of Northern Territory and South Australia with relatively smaller zones in the cores of mountains or highlands in Queensland, New South Wales and Tasmania. New Zealand has no definitely dated Precambrian rocks, but certain metasediments and gneisses in Westland and South Nelson that contain gold-quartz lodes with pyrite, arsenopyrite and stibnite in shears and crushed zones (Westland, Paparoa, Lyell and Reefton goldfields) may be of this age (Williams, 1974). Elsewhere in Australasia rocks of undoubted Precambrian age appear to be rare.

In Western Australia and Northern Territory numerous gold deposits of the gold-quartz type have been mined principally in the Norseman, Kalgoorlie, Coolgardie, Wiluna, Lawlers, Marble Bar, Brocks Creek, Paterson Range and Tennant Creek areas (Edwards, 1953; Blockley, 1974; Knight, 1975). Most of the deposits occur in ancient (Archean) volcanics (greenstones) and their associated sediments and granitic intrusives; in places also in iron-formation. The Tennant Creek gold-copper-bismuth deposits are in lower Proterozoic greywacke and shale interbedded with iron-formation; the oxidized gold quartz orebodies of the Telfer Mine in the Paterson Range are in pyritic slates and quartzites of Middle Proterozoic age. Elsewhere in the Precambrian of Australia gold is won from gold-quartz veins and a variety of massive sulphide and polymetallic bodies, including those at Broken Hill and in the Duchess, Selwyn and Kuridala areas southeast of Mount Isa. The Etheridge goldfield in northern Queensland comprises mainly quartz veins associated with the Forsayth Granite and Cobbold Dolerite, which are intrusive into Archean and Lower Proterozoic schist and gneiss. The mineralization is probably of Proterozoic age (Woodal, 1975) and comprises quartz, pyrite, galena, chalcopyrite and sphalerite. Most of the oreshoots averaged more than 1 oz/ton but were shallow in depth (300 ft). Deposits in quartz-pebble conglomerates are known in the basal members of the Proterozoic Nullagine Series, Marble Bar district, Western Australia, but they are only of marginal economic importance. A few small gold placers, mostly of Tertiary age, derived from the Precambrian deposits, have been worked in Western Australia and elsewhere in Australia. The Precambrian lodes in Westland and South Nelson in New Zealand also gave rise to productive alluvial gold concentrations.

Precambrian rocks probably underlie much of Antarctica as is witnessed by abundant exposures along the margins of the continent, particularly East Antarctica, which is probably a shield area. Most of the Precambrian rocks dated so far in Antaractica appear to be relatively young, 1800 million years or so. No gold deposits have yet been discovered in these rocks.

Gold deposition during Precambrian time has been a long and complex process differing in details in the various shields and other Precambrian terranes of the earth. The writer has studied only the Canadian Shield in detail with respect to gold deposition in Precambrian time. Some of the features of the gold deposits in this vast terrane of rocks are similar to those found elsewhere in Precambrian rocks, but it should also be borne in mind that there are significant differences as well. One striking similarity is the frequent development of deposits of the gold-quartz type in ancient volcanics (greenstones) and their associated sediments, particularly the iron-formations and greywacke-slate sequences. A marked difference is the general absence of economic quantities of gold in the Early Proterozoic uraniferous quartz-pebble conglomerates of the Canadian Shield (e.g., Blind River–Elliot Lake) similar to those developed in South Africa (Witwatersrand), Ghana (Tarkwa) and Brazil (Jacobina). The Canadian Shield is also relatively poor in economic Proterozoic deposits of the gold-quartz type, compared to the Australian, Arabian, African and other shields.

Gold deposition took place in the Canadian Shield during or following all of the four major orogenies as defined by Stockwell (1970, 1973) (Table 29), but the intensity has varied greatly. The greatest and most productive period is related to the Kenoran with minor and weak periods of mineralization associated with the Hudsonian, Elsonian(?) and Grenvillian. Most of the productive gold deposits in the Canadian Shield are in Archean rocks with only minor deposits in Proterozoic rocks. With respect to the structural provinces of the Canadian Shield (Fig. 4), as defined by Stockwell (1970), nearly all of the highly productive gold deposits occur in the Superior and Slave provinces; only a few, relatively small, rich or large low-grade deposits are known in the Churchill, Bear, Southern and Grenville; and no economic deposits are known in the Nutak Province. A summary of the principal characteristics of the gold deposits of the Canadian Shield is given in Table 30.

The Archean rocks of the Canadian Shield are characterized by thick sequences of volcanic flows and various intrusives of basic, intermediate and acidic composition, all generally referred to in the older literature as Keewatin. These are interbedded with or overlain often conformably by great thicknesses of greywackes and allied rocks commonly referred to in the older literature as Temiskaming-type sediments. The Archean volcanic terranes have been much studied over the last 75 years by many geologists. In the writer's opinion they differ little from what one sees in volcanic terranes of more recent vintage. One feature is of great importance in the writer's opinion – the presence, in places, of considerable thicknesses of sulphide-bearing slates, tuffs, graphitic schists and iron-formation (Boyle, 1968*a*, 1976*a*). These are commonly enriched in gold, silver, base metals and other elements found in the epigenetic deposits of the volcanic terranes (Tables 15 and 16). They were probably one of the major sources of the metallic elements, sulphur, arsenic, etc. in the epigenetic deposits of the Archean. Similar enrichments of gold and other metals occur in bands and beds of graphitic pyritiferous rocks in the Timiskaming-type sediments. Considered overall, the Archean piles of volcanic and sedimentary rocks initially contained sufficient enrichments of gold and silver and other metals to provide a source for all of the epigenetic deposits found within them (Boyle, 1976*a*). All of the Archean rocks were folded, sheared, faulted, metamorphosed, granitized and intruded by granitic rocks during the late Archean Kenoran orogeny and possibly older orogenies. The Archean rocks are best preserved in the Superior and Slave provinces but have also been recognized in parts of the Grenville, Churchill, Southern and Nutak provinces.

Table 29. Precambrian time-stratigraphic classification in relation to orogenies of the Canadian Shield

Eon	Era	Sub-Era	Orogeny (mean K-Ar mica age, m.y.)
Proterozoic			
	Hadrynian		
			Grenvillian (955)
	Helikian	Neohelikian	
			Elsonian (1370)
		Paleohelikian	
			Hudsonian (1735)
	Aphebian		
Archean			Kenoran (2480)

Source: Stockwell (1970, 1973).

The Proterozoic rocks of the Canadian Shield are a varied lot, and few generalizations can be made about them. In most regions they comprise conglomerate, quartzite, greywacke, arkose, shale, stromatolitic limestone and other allied sedimentary rocks. In some regions these rocks are present in addition to basic volcanic flows and sills, iron-formation, limestone (marble) and other allied rocks. Some Proterozoic rocks are relatively flat-lying and little disturbed except by faulting and minor folding as in the Cobalt area of Ontario; others are highly folded, faulted, sheared, metamorphosed, granitized and intruded by granitic rocks during the Hudsonian, Elsonian and Grenvillian orogenies.

The gold deposits related to the Kenoran orogeny are developed mainly in shear zones and faults in the Archean volcanic and sedimentary rocks of the Superior and Slave provinces, but some important deposits (e.g., Kirkland Lake) occur in faults in associated intrusive granitic rocks and porphyries in these provinces. Most of the highly auriferous deposits belong to the gold-quartz and disseminated types, but considerable amounts of gold and silver have been won as byproducts from the massive and disseminated sulphide orebodies mined essentially for copper and zinc. The main characteristics of the auriferous deposits related to the Kenoran are shown in Table 30. The principal gangue is quartz with some carbonate, often ankerite. The main metallic minerals are pyrite, arsenopyrite and pyrrhotite, with minor amounts of galena, sphalerite, chalcopyrite, stibnite, molybdenite, scheelite and various sulphosalts. The gold in most deposits is free or combined as a telluride or antimonide (aurostibite). In some deposits the gold is intimately associated with arsenopyrite, pyrite or sulphosalts as a lattice or submicroscopic constituent, and these ores frequently have to be roasted before cyanidation. The characteristic elements accompanying gold vary from place to place, but a generalized association includes Cu, Ag, Zn, Cd, B, Pb, As, Sb, Se, Te, Cr, Mo and W. Not all of these are found in any one deposit. Barite is rare as a major gangue mineral, and fluorite is met with only occasionally. Cobalt and nickel occur in the ores only as traces or minor amounts, and cobalt-nickel minerals are rare in most deposits. Platinum metals are not found except as traces, and then only sporadically. Bismuth is relatively rare in the ores, and uranium and thorium are lacking in more than traces. The rare-earths, likewise, occur in the ores only as traces. Niobium and tantalum are not found, and tin occurs generally only as traces in the ores. Mercury is generally only a trace constituent of the gold, sulphide minerals and sulphosalts. Cinnabar has not been recorded in

Table 30. Characteristics of gold deposits related to principal orogenies of the Canadian Shield

	Kenoran (2480)*	Hudsonian (1735)*	Elsonian (1370)*	Grenvillian (955)*
Structural province affected	Superior, Southern and Slave; parts of Churchill and Grenville	Churchill, Bear and Southern	Nain Subprovince, Grenville Province	Grenville
Age of host rocks	Archean – Keewatin and Timiskaming types of volcanics and sediments and their associated granitic rocks and porphyries	*Churchill Province* Archean – Keewatin and Timiskaming types of volcanics and sediments, their granitized equivalents and associated granitic bodies and porphyries *Southern Province* Proterozoic – Huronian quartzite, greywacke, slate and their metamorphosed equivalents. Post-Huronian diabase		Archean and Proterozoic
Principal types of host rocks	Basic, intermediate and acidic volcanics (greenstones) Greywacke and allied rocks. Granitic rocks and porphyries	*Churchill Province* Basic, intermediate and acidic volcanics and their metamorphosed equivalents. Greywackes and allied rocks and their metamorphosed equivalents including gneisses and schists. Grantitic rocks and porphyries *Southern Province* Quartzite, greywacke, slate and their metamorphic equivalents. Diabase		Amphibolites (greenstones), gneiss, schist, skarn, syenite and gabbro
Principal types of deposits	Gold-quartz veins and silicified zones. Massive and disseminated Cu-Zn sulphide bodies	*Churchill Province* *Flin Flon–Herb Lake area* Gold-quartz; massive and disseminated Cu-Zn sulphide bodies *Lake Athabasca area* Quartz stockwork in granitic sill; disseminated quartz-carbonate-sulphide bodies *Southern Province* Gold quartz veins and stockworks; massive Ni-Cu ores	No deposits known	Gold-quartz veins. Disseminated and vein like bodies in skarn. Cu-Zn-Pb sulphide bodies in skarn
Principal gangue minerals	Quartz, carbonates (mainly ankerite, dolomite and calcite	Quartz, carbonates (mainly ankerite, dolomite and calcite). Quartz and siderite in places in the Southern Province		Quartz, carbonates (mainly ankerite, dolomite and calcite); various skarn minerals
Principal metallic minerals	Pryrite, arsenopyrite and pyrrhotite; minor galena, sphalerite, chalcopyrite, stibnite, molybdenite, scheelite and various sulphosalts	*Churchill Province* *Flin Flon–Herb Lake area* Pyrite, arsenopyrite and pyrrhotite; minor sphalerite, chalcopyrite and galena *Lake Athabasca area* Pyrite, arsenopyrite, chalcopyrite, Ni-Co arsenides, sphalerite and pitchblende *Southern Province* Pyrite pyrrhotite, arsenopyrite; very minor chalcopyrite, sphalerite and galena		Pyrite, arsenopyrite, pyrrhotite, magnetite, ilmenite; variable amounts of sphalerite, chalcopyrite, galena and tetrahedrite
Nature of the gold	Free or combined as telluride or antimonide (aurostibite). Some intimately associated with pyrite, arsenopyrite and sulphosalts	Generally free. In the Flin Flon–Herb Lake area and in the Southern Province some gold is intimately associated with arsenopyrite		Generally free but in some deposits intimately associated with arsenopyrite

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Table 30. (cont'd.)

Characteristic associated elements†	Cu, Ag, Zn, Cd, B, Pb, As, Sb, Se, Te, Cr, Mo, W	*Churchill Province* *Flin Flon–Herb Lake area* Cu, Ag, Zn, Cd, B, Pb, As, Sb, Cr *Lake Athabasca area* Cu, Ag, Zn, Cd, Pb, As, Sb, Se, Mo, U, Rare earths, Hg (Pt), (Te) *Southern Province* Cu, Ag, Zn, Cd, Pb, As, Sb, W	Cu, Ag, Zn, Cd, B, Pb, As, Sb, Co, Bi, F; U; Th and rare earths in some deposits
Characteristic wall-rock alteration processes	Chloritization, silicification, sericitization, carbonatization, tourmalinization, albitization, pyritization and arsenopyritization	Chloritization, sericitization, silicification, carbonatization, tourmalinization, albitization, pyritization and arsenopyritization. Hematitization in Lake Athabasca region	Chloritization, silicification, carbonatization, tourmalinization, pyritization and arsenopyritization. Development of skarn

*Mean K-Ar mica age in millions of years.

†Excluding the common and nearly universal associates such as Si, Fe, S, etc.; elements in parentheses are rare or localized.

the deposits as far as the writer is aware, but mercury tellurides occur in some ores. The Au/Ag ratio of these ores is high as a rule, averaging about 8. Local reversals of the ratio yielding values of 1 or less may occur in ore shoots where silver tellurides, silver-bearing tetrahedrite or a secondary mineralization of silver minerals are present.

The Hudsonian orogeny is manifest mainly in the Churchill, Bear and Southern provinces. Gold deposits in these provinces tend to be small or have large tonnages with very low grades; some of the smaller deposits are exceptionally rich. In Churchill Province most of the gold deposits belong to the gold-quartz type and are clustered in the Flin Flon–Herb Lake belt of volcanics and sediments which may be of Archean age. Those at Nor-Acme, Laguna, Gurney and Squall Lake are thought by some geologists to be related to the Kenoran orogeny, which has been affected later by the Hudsonian. On the north shore of Lake Athabasca the Box Mine was developed in a granitic sill that appears to intrude or was derived by granitization from the Tazin Group of sediments, which are thought to be of Archean age. In the same area the Nicholson Mine, originally prospected for gold, occurs in dolomite, calcareous quartzite and ferruginous quartzite of the Tazin Group intruded by an amphibolite sill. South of Lake Athabasca in the Carswell structure one of the Cluff Lake uranium deposits is enriched in gold and gold tellurides. Elsewhere in the Churchill Province numerous gold-quartz veins are known, but none are of importance economically. Considerable amounts of gold have been won from massive and disseminated Cu-Zn ores in volcanic and sedimentary terranes in the Churchill Province.

The character of the gold-quartz deposits in the Churchill Province are essentially the same as those mentioned for the Superior and Slave provinces. There are, however, a few minor differences in their elemental contents in the Flin Flon–Herb Lake area, and in the Athabasca region. The gold ores in the Flin Flon–Herb Lake area appear to be low in tellurides and hence tellurium, although this element occurs in the Flin Flon massive Cu-Zn sulphides and in other similar bodies in the area. Molybdenum and tungsten, likewise, appear to be particularly low in abundance. In the Lake Athabasca area the orebodies of the Box Mine contain some pitchblende, and those at the Nicholson Mine contain pitchblende, thucholite, Co-Ni arsenides, a variety of silver minerals and tiemannite (HgSe). Platinum has also been recorded in the ores. The Cluff Lake deposit, enriched in gold, carries abundant pitchblende, clausthalite (PbSe), Ni-Co arsenides and copper sulphides. There is some platinum in the deposit. All of these mines occur in the Athabasca uraniferous belt, and it is difficult to determine the relative ages of the gold and uranium mineralization. The gold mineralization may be earlier than the uranium one, although examination of samples suggests they are often contemporaneous; in some samples the gold is late.

There are no known economic gold deposits in the Bear Province. Lord (1951) mentions only one significant occurrence of gold in this province, on Norris Lake about 145 mi north-northwest of Yellowknife (Doris Yellowknife Gold Mines Ltd.). The occurrence is mainly in Proterozoic black slate and argillite of the Snare Group. The mineralization occurs in contorted shear zones and consists of quartz stringers and lenses with some carbonate and abundant pyrite, galena, sphalerite, arsenopyrite, pyrrhotite and chalcopyrite. According to Broughton (1973) there are about 81 000 tons of ore containing 0.228 oz Au/ton in this deposit. Numerous other quartz veins and other types of deposits carry traces of gold in other areas of the Bear Province including the Oro, Bud and Thompson occurrences on Great Bear Lake (Lord, 1951). None of these were of economic interest as gold deposits when Lord examined them.

The gold deposits and occurrences in the Southern Province occur in highly folded and contorted Huronian (Proterozoic) quartzites, greywackes and slates, their metamorphic equivalents, and in associated granitic rocks; also in (Nippissing?) diabase and gabbro, which intrudes the Huronian rocks throughout the area north of Lake Huron. There are also some gold-quartz veins in greenstones that are probably of Huronian age southwest of the early Middle Proterozoic Sudbury irruptive. The Sudbury ores, associated with norite, gabbro and associated rocks, contain some gold and silver, the average contents being about 3.5 ppm Au and 45 ppm Ag in the massive sulphides and 0.08 ppm Au and 2.3 ppm Ag in the ore as mined. One deposit south of the irruptive (the Vermilion Mine), essentially a massive pyrite-chalcopyrite body, was

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enriched in gold, silver and platinum minerals. Analyses of massive pyrite and chalcopyrite taken from the old dumps of this mine contained the following amounts of precious metals in ppm: Au 1.9, Ag 100, Pt 35 and Pd 108. Quartz veins in the near vicinity of this deposit, mineralized with small amounts of pyrrhotite and chalcopyrite, are low in the precious metals, representative analyses being as follows in ppm: Au 0.055, Ag 1.0, Pt<0.005, and Pd 0.008.

The gold deposits in the Southern Province belong mainly to the gold-quartz type. The principal gangue is quartz with some carbonate, often ankerite, dolomite or siderite (Crystal Mine on Lake Wanapitei). Barite is present in a few deposits; fluorite appears to be absent. The principal metallic minerals are pyrite, arsenopyrite and pyrrhotite, with very minor amounts of chalcopyrite, sphalerite, galena and native arsenic and/or native copper in some deposits. The gold is mainly free, but some is intimately associated with arsenopyrite. The characteristic elements accompanying gold vary from place to place, but a generalized association includes Cu, Ag, Zn, Cd, Pb and As. Sb, Te, Mo, Co, Ni, W, Ba, Sr and Se are present in trace and minor amounts in some deposits. Pt, Pd, U and Sn were not detected in analyses of ores done for the writer from various veins in the area west of the Sudbury irruptive to Sault Ste. Marie. The deposits include those on Lake Wanapitei (Crystal Mine); the Havilah (Ophir) north of Thessalon; prospects on Howry Creek (Bousquet Mine); and occurrences in the Whiskey Lake area. The Bruce Copper Mines, which are in Keweenawan diabase, were fairly regular quartz veins containing chalcopyrite and small quantities of calcite and barite; they also carried a little gold in places, up to 2.5 oz/ton in some pockets. Descriptions of these various deposits are given by Hopkins (1922), Bruce (1933) and Kindle (1936).

The Southern Province also contains the extensive pyritiferous quartz-pebble conglomerates of the Matinenda Formation of the Elliot Lake Group (Early Proterozoic) in the Blind River–Elliot Lake district of Ontario. These contain large tonnages of uranium ore, but their gold tenor, unlike those of the Witwatersrand is measured only in minor and trace amounts. The average gold and silver contents of typical ore are 0.1 and 2.7 ppm respectively. The pyrite may contain up to 0.4 ppm Au and 9 ppm Ag.

The Elsonian orogeny appears to have affected principally the Nain Subprovince of the eastern Churchill Province and extended through much of the Grenville Province. So far as is now known there are no economic gold deposits related to this orogeny. Even gold occurrences seem to be absent or sparse.

The Grenvillian orogeny is manifest in the Grenville Province. This province is a complex mixture of rocks of the various Precambrian eras including both Archean and Proterozoic types. Greenstones (now mainly amphibolites and granulites) occur in some areas, but the most characteristic rocks are paragneiss, schist, marble and skarn. There are also large areas of quartzite, slate, metamorphosed iron-formation and allied rocks. All of these rocks are intruded by pegmatites, granites, syenites, nepheline syenites and anorthosites, the origin of which has long been problematical. Most of the granitic types and the ordinary syenites seem to have been derived by a process of intense granitization of the sediments. The others may have been derived by some uncharacterized process related to deep-seated differentiation.

Four types of gold-bearing deposits occur in the rocks of the Grenville Group: gold-quartz veins and stringers in gabbro (Cordova Mine); similar bodies in carbonatized amphibolite, epidotized rock, hornblende schist, greywacke and dolomite; skarn-type bodies (Richardson and other deposits); and auriferous skarn deposits mined essentially for their Cu, Pb and Zn contents (New Calumet and Tetreault deposits).

The gold-quartz and skarn-type deposits of eastern Ontario occur in the belt of Grenville rocks extending from Belmont Township, Peterborough County eastward across the counties of Hastings, Addington and Frontenac into the western part of Lanark County, in all a distance of about 70 mi. Gold was first found in Ontario in this belt near Eldorado (Richardson Mine). A large number of deposits are known, but most are small and low grade, although some were exceptionally rich near the surface. Descriptions of the deposits can be found in the reports of Vennor (1870), Miller (1902), Miller and Knight (1914), Hopkins (1922), Hurst (1927), Rickaby (1932) and Cooke (1946). Most deposits consist mainly of quartz veins, silicified zones or irregular skarn-type bodies, some with abundant arsenopyrite with which the gold is often closely associated. Other common minerals include pyrite, ankerite, pyrrhotite, tourmaline, feldspar, fluorite, chalcopyrite, tetrahedrite, galena, magnetite and ilmenite. The Richardson Mine is interesting from a scientific viewpoint in that some of the gold occurs in thucholite or is associated with uraninite and brannerite. The Au/Ag ratio in all of these deposits is generally greater than 1 and appears to average about 10 according to my analyses.

The auriferous skarn-type deposits mined essentially for Cu, Pb and Zn, including New Calumet and Tetreault in Quebec, contain essentially pyrite, galena, sphalerite, chalcopyrite and tetrahedrite in a gangue of skarn minerals. Free gold and electrum occur in the ores. The Au/Ag ratio is invariably less than 1.

Paleozoic

The Paleozoic is that era of geologic time between the Precambrian and Mesozoic eras and comprises rocks belonging to the Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian and Permian systems. The Paleozoic era is generally considered to have been closed by orogenic disturbances known by various names throughout the world – the Appalachian in eastern North America, the Hercynian (Variscan) in Europe and so on (Fig. 5). There are also a number of other orogenies that have affected Paleozoic rocks at various times, e.g., the Acadian in eastern North America, which occurred in Devonian time, and the Caledonian in Europe, which is of Siluro-Devonian age. Space does not permit discussion of the various Paleozoic orogenies throughout the world, but reference will be made to those that are of interest with respect to gold mineralization.

Paleozoic rocks, mainly sediments with local centres of volcanics, were laid down over much of the North American continent. Those in the central parts of the continent suffered relatively little disturbance during Paleozoic time, and no epigenetic gold deposits are known in these rocks. In the Cordillera there is evidence for a widespread orogeny in Devonian time and possibly also in late Permian time. Evidence for these orogenies is most clearly seen in parts of

British Columbia, in the Antler Peak region of Nevada, and elsewhere in western United States and Mexico. It appears, however, that the effects of the Paleozoic orogenies in the western Cordillera are not readily separated from those that took place during Mesozoic and Cenozoic times. In any case there are no epigenetic gold deposits known to be associated with these supposed Paleozoic orogenies of the western Cordillera. Gold deposits do occur, however, in the Paleozoic rocks in places in the western Cordillera, but they are related to Mesozoic and Tertiary orogenies and are discussed below. In the northern part of the continent, in the Arctic Islands, the Paleozoic rocks of the Innuitian orogen suffered several periods of orogenic disturbance but were not extensively granitized or injected by granitic rocks. No gold deposits are known in these rocks. The Paleozoic rocks flanking the eastern coast of the continent were highly folded, faulted, granitized and intruded by granitic rocks during two main orogenic events, the Acadian and Appalachian. Gold deposition is associated principally with the Acadian orogeny of Devonian age.

In the southern Appalachians of the United States a number of gold belts extend from the Potomac River near Washington, D.C. to Alabama (Becker, 1895; Lindgren, 1933; Pardee and Park, 1948). The deposits belong mainly to the gold-quartz type and are veins or irregular silicified and pyritized bodies. They occur in slates, schists, gneisses, amphibolites, altered volcanic tuffs and breccias and a variety of granitic rocks, all of which range in age from Precambrian to middle Paleozoic (Devonian?). Some think the deposits are of late Paleozoic age, but the results of geochemical and geological studies by Bell (1960) in the Concord area suggest two periods of mineralization. The gold is apparently related to the earlier period which is associated with small granite plutons, possibly older than Devonian(?). The characteristic gangue is quartz with carbonates, biotite, chlorite, magnetite, ilmenite, tourmaline, albite, gahnite, garnet and minor barite. Fluorite is rare. The metallic minerals are pyrite, arsenopyrite, pyrrhotite, molybdenite and less commonly ferberite, scheelite, galena, sphalerite, tetrahedrite and chalcopyrite. The gold is generally free; a few tellurides (tetradymite, altaite and nagyagite) have been recorded. The principal elements enriched in the deposits in addition to gold are Cu, Ag, Ba, Zn, Cd, B, Pb, As, Sb, (Bi), (Te), Mo and W. Those in brackets are relatively rare. The Au/Ag ratio of the ores appears to range from 5 to 8. Placers derived from these deposits have been worked in the past.

Another belt of auriferous deposits occurs throughout the length of the mainland of Nova Scotia mainly in Ordovician rocks (Meguma Group). These rocks are mainly greywacke, quartzite, arkose, and slate which have been metamorphosed, granitized and intruded by Devonian granitic rocks related to the Acadian orogeny. The gold deposits belong to the gold-quartz type and are developed mainly as veins and saddle reefs (Bendigo type) (Malcolm 1912; Malcolm and Faribault, 1929; Douglas, 1948; Bell, 1948). The principal gangue is quartz with minor amounts of carbonates; the metallic minerals are pyrite, arsenopyrite, chalcopyrite, galena, sphalerite, stibnite, tetrahedrite, scheelite and molybdenite. The gold is generally free, but some is closely associated with arsenopyrite. No tellurides are recorded; only traces of Te and Se have been found in the ores by the writer. The Au/Ag ratio in these deposits ranges from 1.5 to 5.5 in most deposits, but values as high as 50 or more are recorded from some veins. The elements enriched in the deposits in addition to gold include Cu, Ag, Zn, Cd, B, Pb, As, Sb, Mo and W.

Gold-quartz deposits similar to those in Nova Scotia and the southern Appalachians of the United States are widespread throughout the Paleozoic rocks of Newfoundland (Snelgrove, 1935), New Brunswick, Gaspé and Eastern Townships of Quebec, Green Mountains of Vermont and the New England states. There are also gold-quartz veins and gold-bearing silicified zones in Precambrian rocks in Cape Breton Island (Baddeck area), southern New Brunswick and elsewhere in the Appalachians. As noted previously, these are probably of Precambrian age. All of these deposits in both Precambrian and Paleozoic rocks are small and generally low grade according to the writer's observations. Some gold is won as a byproduct of massive and disseminated Cu-Zn-Pb ores in Paleozoic rocks in Newfoundland, New Brunswick, Quebec and the Appalachian regions of U.S.A. In these deposits the Au/Ag ratio is invariably less than 1 by a large factor.

Tertiary and Quaternary placers derived from the Paleozoic deposits just described have been worked in the past in Quebec and Nova Scotia. Most were small, but those in the Chaudière valley of Quebec were of moderate size and relatively rich. Ancient (fossil) placers in Carboniferous rocks derived from gold deposits in rocks of Devonian age or older are known in Nova Scotia at Gays River and at Nauwigewauk in New Brunswick. These are small and low grade where observed, but they should receive further investigation since larger and richer bodies may lie beneath the thick drift cover. (*See also* the section on placers.)

The continent of South America is not marked by gold deposition related to Paleozoic orogenies. Paleozoic rocks are, however, widespread in South America and are metamorphosed, granitized and intruded by granitic rocks in places, particularly in Colombia. No gold deposits of economic interest seem to be definitely related to Paleozoic orogenies in the Cordillera as far as the writer can ascertain. The rich gold deposits of Colombia, so avidly sought by the Conquistadores, while in rocks as old as Precambrian, are mainly of Tertiary age or placers derived from epigenetic deposits of that age.

In northwestern Argentina, from the Bolivian border to a point south of Mendoza, there is a belt of gold deposits of uncertain age in schists, gneisses and various types of sedimentary and volcanic rocks. A number of the deposits are said to be related to Paleozoic or older granites, and some are associated with Tertiary igneous rocks. Probably most of the gold deposits are of Tertiary age (Whiting, 1959). A number of the deposits are quartz veins and stockworks; others are silicified zones and stockworks. The principal gangue minerals are quartz and carbonates with pyrite, arsenopyrite, stibnite, galena, sphalerite, chalcopyrite, tetrahedrite, enargite, famatinite and chalcocite. The gold is free in most deposits. Many of the deposits are deeply oxidized and enriched in both gold and silver. Placers derived from the deposits have been worked in some districts.

Africa is underlain in places by a variety of Paleozoic rocks, and these are folded, faulted, granitized and intruded by granitic bodies related to the Hercynian and earlier

Paleozoic disturbances, particularly in the Atlas and Anti-Atlas ranges which suffered their greatest deformation during the great Alpine (Tertiary) orogeny. The gold deposits of Morocco are mainly in Precambrian rocks but may be of Hercynian age according to Jouravsky (1952*a*). Most of the deposits are hematitic gold-quartz veins and lodes with pyrite, arsenopyrite, pyrrhotite, galena, sphalerite, chalcopyrite, chalcocite and native gold. Those in the Bou Azzer region are unusual in that the native gold is in or associated with brannerite, chalcopyrite, pyrite and a great assemblage of cobalt-nickel arsenides in a gangue of calcite, dolomite, quartz, talc and chlorite. In the Cape System of South Africa gold-quartz veins with minor amounts of galena, chalcopyrite and marcasite occur in the much disturbed Paleozoic terrane of Knysna and in a broad zone of crushing at Hell's Gate in Alfred County, Natal.

In Europe, the Caledonian and Hercynian orogenies are manifest in Paleozoic rocks in three great belts. On the northwest, the older Lower Paleozoic Caledonian orogenic belt extends southwestward through Scandinavia into the northern and western parts of the British Isles. On the south the Hercynian orogenic belt appears in a great series of massifs, the intervening parts being buried by younger rocks, which extends from southern Ireland and Cornwall through France and the Iberian peninsula eastward to the region north of the Sea of Azov. The third belt occurs along the site of the Urals and extends northward to Novaya Zemlya. In these belts the Paleozoic rocks are highly folded, faulted, granitized and intruded by granitic rocks. Tin, lead, zinc, copper, silver, arsenic and antimony predominate among the metals deposited during the orogenies that built these belts. Gold deposits figure only in places, particularly in the Urals, but also in Wales and elsewhere in Europe.

In Wales, the Romans mined gold from a number of gold-quartz veins and lodes near Llandovery (Ogofau workings) (Nelson, 1944). The most important Welsh deposits, now exhausted, are, however, in Merionethshire in the Mawddach Valley, north of Dolgellau (Andrew, 1910*b*; Thomas, 1961; Collins, 1975; Hall, 1977). The deposits are gold-quartz veins and lodes related to the Caledonian orogeny. They occur in highly folded and faulted Cambrian black slates, quartzites, phyllites and schists, highly pyritiferous in places, and intruded by diorite, dolerite and diabase dykes, sills and plugs. The principal gangue is quartz with minor carbonates (mainly calcite). The metallic minerals include pyrite, arsenopyrite, pyrrhotite, sphalerite, galena and chalcopyrite. Tetradymite, the bismuth telluride, is reported as occurring in some veins. The gold is generally free, and the Au/Ag ratio of the deposits is about 9.5. Copper deposits occur in the same area, and a porphyry-type (disseminated) copper deposit has been recently discovered near some of the old gold workings.

Gold has been won from veins and placers in the Leadhills district and elsewhere in Scotland and in several places in Ireland, mainly County Wicklow (Atkinson, 1619; Reeves, 1971; Collins, 1975), the gold being probably derived from scattered gold-bearing quartz veins and sulphide deposits in Paleozoic rocks affected by the Caledonian orogeny. Other gold-quartz veins and base metal lodes, containing a little gold and related to the Hercynian orogeny, are known in various places in western Europe – in Cornwall and Devon in England and in Portugal, Spain, France, Czechoslovakia and Germany. Most of these deposits are small, but they probably contributed much gold to the Tertiary and Quaternary placers worked by the Romans and described by Strabo, Diodorus and Pliny.

A few deposits in Norway and France have provided a moderate amount of gold. In Norway gold-quartz deposits in a variety of Paleozoic rocks occur on Bömmel Island, southern Norway, and in the Bindalen district (Vokes, 1958). In France gold has been won from deposits at La Lucette, La Bellière, Châtelet, Cheni, La Gardette and in the district of Salsigne (Aude). Most of the deposits are quartz veins and lodes in schists and gneisses intruded by granitic rocks. The gold deposits of the Salsigne district (Tollon, 1970) are in complexly folded Paleozoic limestones, shales and grits. They constitute veins and replacement bodies containing quartz, arsenopyrite, pyrite, pyrrhotite and chalcopyrite. Among a number of other minerals present are bismuth, bismuthinite, galena and sphalerite. The deposits of the St. Yrieix district in the Massif Central (Cheni, La Fagassière-Les Gareillas) are veins in schists, gneisses, tonalites and granites (Sevensma 1941; Normand and Phan, 1968). The mineralization is quartz, arsenopyrite, pyrite, galena, sphalerite, jamesonite-boulangerite, chalcopyrite, pyrrhotite, stibnite, tetrahedrite, bournonite and native gold. Some of the apophyses of the granitic bodies contain specks of free gold in tiny quartz veinlets. This gold is associated with cassiterite, scheelite, pyrite, arsenopyrite and a few other sulphides. At Châtelet the veins contain quartz, pyrrhotite, pyrite, marcasite, arsenopyrite, berthierite, stibnite and carbonates. The gold is never native in this deposit as has been shown by microprobe analysis (Aubert *et al.,* 1964; Burnol *et al.,* 1974). Rather the gold apparently occurs in layers of the arsenopyrite either in lattice sites or in an extremely finely divided form.

Some of the gold deposits in the Armorican Massif (Brittany) may be of Precambrian age according to Guigues and Machairas (1972). This may also be the case for some of the other (generally minor) gold deposits of eastern Europe in the various massifs.

Numerous gold deposits occur in the region southwest of Prague, Czechoslovakia, and these have been mined extensively in the past. The richest occur in the Jilové district where veins and stockworks cut mainly Precambrian greenstones and sediments but are of Hercynian age related to the central Bohemian pluton (Morávek, 1971). The principal gangue is quartz and carbonates mineralized with pyrite, arsenopyrite, pyrrhotite, molybdenite, galena, chalcopyrite, sphalerite, tetrahedrite, meneghinite, bournonite, boulangerite, cubanite, native bismuth, bismuthinite, kobellite, cosalite, native arsenic, scheelite, native gold and tellurides, including tetradymite, tellurobismuthite, calaverite, petzite, hessite, altaite and coloradoite. The veins exhibit several stages of mineralization. The fineness of the gold ranges from 850 to 900.

In Austria deposits of a similar nature and probably of Hercynian age occur in the Hohe Tauern, a region of crystalline gneisses, schists and quartzites invaded by the Ankogl gneissic granitic mass, some 45 km long and 20 km wide. Most of the deposits occur near Rauris, Fusch, Heiligenblut, Döllach, Gastein and Murwinkel. They comprise vein systems and impregnation lodes in gneiss, quartzites and various schists, and contain mainly quartz, dolomite, tourmaline, arsenopyrite, loellingite, pyrite, chalcopyrite, galena, stibnite, argentite, sphalerite, molybdenite, scheelite and gold. The ores, now exhausted averaged about 0.25 oz Au/ton. The silver content was high, averaging 2 oz or more per ton. Much of the gold was free, but some was closely associated with arsenopyrite. The oxidized parts of the lodes were probably very rich; old reports mention up to 500 g/ton or more. Old descriptions of these deposits and others in Austria are given by Beyschlag *et al.* (1914, 1916) and Emmons (1937).

The characteristic elements concentrated in the gold deposits related to the Caledonian and Hercynian orogenies in western Europe are essentially similar and comprise Cu, Ag, Zn, Cd, B, Pb and As. Co and Ni occur in small amounts in some of the deposits in Wales and Switzerland. Te is relatively rare, but Sb and Bi are abundant in places, especially in some of the deposits in Portugal and France (Le Châtelet, La Lucette, Salsigne). Mo, W and Sn are abundant in other types of deposits related to the Paleozoic orogenies but relatively rare in the typical gold deposits.

Gold occurs at many places along the Ural chain, mainly on its eastern flank (Mushketov, 1930; Sirin, 1963; Smolin, 1970; Ovchinnikov, 1972; Borodaevskaya and Rozhkov, 1974). Placers were formerly the main type of deposit, being derived mainly from a great variety of gold-quartz veins and pyritized silicified zones in highly folded and faulted gneisses, schists, phyllites, quartzites, listwänites (quartz-sericite-talc-calcite-dolomite rocks, derived from the alteration of serpentinites and associated intrusives including serpentinites, gabbro, norite and diabase), granite, syenite, various types of porphyries and highly altered (sericitized and pyritized) fine-grained granitic rocks called beresites. The endogene gold deposits are of Hercynian age. In the northern and central part of the Urals the gold deposits appear to show a close relationship to the acidic types of dykes and other intrusions. At Berezovski many of the gold-quartz deposits are ladderlike veins in the beresitic rocks. In the southern part of the Urals there appears to be a closer relationship with the intermediate and basic dykes and other intrusives. The Kochkar deposit is a series of quartz veins and lenses associated with highly altered 'tabashki' dykes, which are meso- and melanocratic rocks consisting principally of biotite, amphibole, feldspars, epidote, quartz and carbonates characterized by a blastic structure. The veins and lenses are most productive where they occur in shears, fractures and altered zones in the 'tabashki' dykes. The principal gangue in most of the typical gold deposits of the Urals is quartz with some carbonates; tourmaline is present in places. The metallic minerals include pyrite, arsenopyrite, pyrrhotite, chalcopyrite, galena, tennantite-tetrahedrite, boulangerite, bournonite, stibnite, aikinite, tetradymite, bismuthinite, etc. Cinnabar is recorded from a few deposits, and scheelite is mentioned as a fairly abundant mineral in one district. The gold is generally free and the Au/Ag ratio of most deposits ranges from 7 to 9. Tellurides appear to be relatively rare. The grade of the deposits is about 10 g/ton (0.34 oz Au/ton). The alteration processes are chloritization, sericitization, silicification, carbonatization, pyritization, beresitization and listwänitization. The characteristic elements concentrated in the gold deposits in addition to gold are Cu, Ag, Ba, Zn, Cd, Hg, B, Pb, As, Sb, Bi, (W), (Ni) and (Co). Those in parentheses are minor or rare.

Prior to the Russian revolution numerous placers and hypogene gold deposits were worked in the Urals. Following the revolution there was a general decline, and little gold mining was done in the area. In the last 30 years a number of new mines have been developed mainly in the Berezovski, Kochkar, Plast-Miass and Dzhetygara areas. The central and southern Urals are also noted for their Hercynian polymetallic and massive and disseminated pyritic Cu-Zn-Pb bodies (Sverdlovsk, Karabash, Bajmak-Sibai, Mednogorsk-Orsk and Kurosan areas). Gold is won as a byproduct from some of these deposits.

The gold placers of the Urals, derived from the deposits of Paleozoic age, were formed during succeeding eras. They include fossil Mesozoic placers and Cenozoic (Tertiary and Quaternary) placers. Many of them produce platinum metals in addition to gold. (*See also* the section on placers.)

In Asia the Caledonian, Hercynian (Variscan) and other minor Paleozoic orogenies were attended by widespread gold mineralization. The Caledonian orogeny is manifest mainly in western Kazakhstan and neighbouring Kirghiz S.S.R., particularly in the regions south and west of Alma-Ata and north and northwest of Lake Balkhash in the Altai-Sayan ranges of Siberia, Mongolia and northwest China and in the Ulan Ude-Chita region (Transbaikal). Hercynian (Variscan) orogenic events are manifest in great belts that extend through Uzbekistan, and the Lake Balkhash and Lake Zaysan regions in Kazakhstan, U.S.S.R., eastward and southward across Mongolia and China into parts of the Malay Peninsula. These great belts of Caledonian and Hercynian disturbances are marked by a large number of productive gold deposits of many types.

Gold was won from placers and mines in Uzbek, S.S.R. long before the Christian era, the mines being mentioned by Strabo and Herodotus in their writings. Today, the birthplace of one of the first of the geological fraternity, Abu Ali Ibn Sina (Avicenna) (980–1037) is one of the foremost gold-producing areas in the Soviet Union. Many deposits are known in the great belts of Paleozoic rocks that stretch from the southern Urals to the T'ien Shan mountains and include the Nuratau Mountains, the Kyzyl-kum desert and Hissar range in Uzbek, S.S.R. The deposits belong mainly to the gold-quartz type and are generally enriched in arsenic. Prospecting in the late 1950's using geochemical methods and arsenic as indicator, led to the discovery of the great Muruntau deposit in the Muruntau Mountains. This deposit is localized in gently dipping metamorphosed sediments on the south limb of an anticline between two large faults. The deposit is a vast stockwork of quartz-pyrite and quartz-arsenopyrite stringers and veins in interbedded metamorphosed carbonaceous sandstones, siltstones, shales, phyllites and a variety of schists some of which are chloritic, all invaded by swarms of granitoid dykes, including various porphyries, granite, syenite and monzonite, apparently all of Hercynian age. The wall-rock alteration is unusual for gold deposits of this type. It includes essentially the development of a hornfelslike (cherty) rock consisting of quartz, biotite, feldspar, sericite, chlorite, actinolite, with pyroxene and hornblende in places. The principal gangue minerals are quartz, feldspar and tourmaline. The main metallic minerals are pyrite, arsenopyrite, pyrrhotite and chalcopyrite. The average sulphide content of the ore is about 1 per cent. Minor and rare minerals include marcasite, scheelite, sphalerite, galena, bismuthinite, native bismuth, cinnabar, miargyrite, tetrahedrite, pyrargyrite and others. The gold is generally free; gold tellurides are suspected. The Au/Ag ratio of the native gold is 94/4; in the deposit as a whole the ratio is 4:1. The grade of the deposit is not stated clearly in the various publications but is probably about 3.4 ppm (0.1 oz/ton). The elements enriched in the deposit include the following in addition to gold: Cu, Ag, Sr, Ba, Zn, Cd, Hg, B, Pb, As, Sb, Bi, Se, Te, Mo, W, Co and Ni. An extended description of the deposit is given in the book edited by Khamrabaev (1969).

In addition to the deposit just described there are various other types of gold deposits in Uzbekistan. According to Petrovskaya (1968) and Khamrabaev (1969) these include quartz-gold-telluride deposits, pyritic quartz deposits with gold and tellurides, quartz-carbonate-adularia-gold (electrum) and skarn-chalcopyrite-gold deposits. The elements concentrated in these deposits are essentially the same as those mentioned for the Muruntau deposit. In places Sb and Te figure more prominently, whereas in others Cu, Mo and W are relatively abundant in the ores.

Northeastward in the Paleozoic rocks of Kazakhstan and in the region west and east of Lake Baikal there are a large number of gold deposits belonging to the following types – skarn, gold-quartz-pyrite-arsenopyrite veins and lodes and various polymetallic deposits enriched in gold and silver. The characteristic elements associated with gold in these deposits include: Cu, Ag, Ba, Zn, Cd, Hg, B, Pb, As, Sb, Bi, Se, Te, Mo and W. Extended descriptions of the deposits in northern Kazakhstan are contained in the papers by Esenov *et al.* (1968, 1970) and the book edited by Abdulkabirova *et al.* (1971).

Gold deposits – mainly of the gold quartz type, but also including the skarn type and gold-bearing polymetallic deosits – occur in Paleozoic rocks in Mongolia, in Manchuria and in the Caledonian and Hercynian belts in China (mainly in Szechwan, Hunan and Kwang-si provinces). There are also a few gold-quartz and skarn-type gold deposits and gold-bearing polymetallic deposits in Paleozoic rocks in Korea and Japan that are probably of Hercynian age. These deposits are, however, relatively insignificant compared with those formed in Japan during the Tertiary.

In Australasia there were two periods of Paleozoic orogeny confined mainly to Australia (Tasman Geosyncline). One marked the period between the close of the Ordovician and the close of the Devonian and appears in places to have affected Silurian rocks as well (the Siluro-Devonian orogeny of Hills, 1947). In Tasmania the age of the granitic intrusives of this period ranges from 375 to 335 m.y. (Late Devonian to Early Carboniferous) (Williams *et al., in* Knight, 1975). In Victoria and New South Wales the age of the granitic intrusives is mainly Siluro-Devonian (Spencer-Jones and Vandenberg, *in* Knight, 1975; Pogson, *in* Knight, 1975). The other period of orogeny and granitic intrusion is Permo-Triassic. To the first belong the rich gold-quartz deposits of Victoria (Bowen and Whiting, *in* Knight, 1975) and adjacent parts of New South Wales (Markham, *in* Knight, 1975) and those in Tasmania (Green, *in* Knight, 1975). Here belong the great gold-quartz lodes of Bendigo, Castelmaine, Ballarat, Daylesford, Hill End, Hill Grove and others. Bendigo and Ballarat are the leading fields. Much gold is also won from the copper sulphide deposits of Cobar, New South Wales (Rayner, 1969; Brooke, *in* Knight, 1975) and from other polymetallic deposits related to the Siluro-Devonian orogeny.

At Bendigo and Castelmaine the rocks are Ordovician slates and greywackes intruded by Devonian granite. The deposits are mainly quartz saddle reefs and bedding plane veins. At Ballarat the deposits are mainly persistent quartz veins in fissures, shears and faults that cut Ordovician slates and greywackes. They are exceedingly rich where they cross indicators (carbonaceous and pyritiferous beds). The deposits at Daylesford are veins and lodes in closely folded Ordovician slates, quartzites and greywacke. In the belt between Walhalla and Woods' Point quartz veins form ladders in diorite dykes or occur in fractures and faults in an area of closely folded Silurian sediments intruded by granodiorite. The principal gangue in all these deposits is quartz with minor carbonates. The main metallic minerals are pyrite, pyrrhotite, arsenopyrite, chalcopyrite, galena, sphalerite and minor molybdenite, wolframite, native bismuth, stibnite, bournonite and other sulphosalts. Some of the deposits are relatively rich in sulphides (up to 60% of the ore). There is little or no wall-rock alteration. The gold is free and no tellurides have been reported. The Au/Ag ratio is high, ranging from 7 to 9. The characteristic elements concentrated in the veins in addition to gold include: Cu, Ag, Zn, Cd, Pb, As, Sb, Mo and W.

At Hill End, north of Bathurst in New South Wales, lenticular quartz veins occur in Silurian slates and tuffs intruded by quartz porphyry. At Hargraves the deposits are saddle reefs. In the Hill Grove area in the northeastern part of New South Wales gold-quartz veins occur in slates and greywackes. The gangue is invariably quartz and minor carbonate in all of these deposits with subordinate amounts of pyrite, arsenopyrite, pyrrhotite, galena, sphalerite, stibnite and minor scheelite. The characteristic elements concentrated, in addition to gold, include Cu, Ag, Zn, Cd, Pb, As, Sb and W.

Most of the gold-quartz deposits of Tasmania are related to the Siluro-Devonian period of orogeny and are located in the northeast part of the island (Green, *in* Knight, 1975). The deposits at Lisle-Golconda, Mathinna, Mangana and Beaconsfield are quartz veins and pyritiferous quartz veins mainly in fissures, faults and shears in folded Ordovician conglomerates, limestones, quartzites, slates and various schists and serpentinites intruded by granite, granodiorite and a variety of porphyrites. Elsewhere in Tasmania there are other gold-quartz deposits and polymetallic deposits carrying small amounts of gold. The famous Mount Lyell and nearby deposits, 15 mi northeast of Strahan, are some of the world's greatest copper-gold deposits (Reid, *in* Knight, 1975). The Mount Lyell deposit was a massive sulphide body, greatly enriched at the surface in gold, contained within sericite schists (acid lavas and pyroclastics) near a conglomerate contact. The primary ore consisted principally of pyrite, chalcopyrite, a little bornite, enargite, galena, sphalerite, molybdenite and tennantite with a little quartz, fluorite and barite. In summary, the characteristic elements concentrated with gold in the deposits related to Paleozoic orogenies in Tasmania include Cu, Ag, Ba, Zn, Cd, Pb, As and Sb. Sn and

W occur in some gold-bearing lodes, and F is recorded in places.

Paleozoic rocks, highly deformed and intruded by granitic batholiths of Devonian and Permo-Triassic age characterize the mountain ranges of Queensland and northeastern New South Wales and extend along the coast for some 1400 mi (Murray, *in* Knight, 1975). Associated with the Paleozoic orogenies are a number of important gold districts some still productive, including Capetown (Charters Towers), Mount Morgan, Gympie, Mount Coolon, Mount Taylor, Palmerville, Ravenswood, Croydon, Cracow, Hodgkinson and others. The first three have produced the largest amounts of gold. Most of the deposits are gold-quartz veins and lodes in slates, quartzites, limestone, various schists, volcanics, porphyries and granitic rocks. The gangue is quartz with minor carbonates, and the metallic minerals are mainly pyrite, pyrrhotite, arsenopyrite, sphalerite, galena, chalcopyrite, stibnite and tennantite-tetrahedrite. Gold also occurs in some quantity in a variety of skarn deposits that contain essentially the same minerals noted above in addition to bornite, bismuthinite, native bismuth, magnetite, etc. A variety of polymetallic deposits also contain considerable gold, which is won as a byproduct. The great quartz-pyrite-chalcopyrite stockwork pipe with massive and disseminated sulphide zones in quartz porphyries (volcanics) at Mount Morgan, highly enriched in gold in the surface oxidation zones, is an example of these types of deposits. Most of the gold in the Queensland deposits is free, but some is intimately associated with fine pyrite and arsenopyrite. Gold and silver tellurides occur at Charters Towers, Gympie and Golden Plateau at Cracow. Some of the Queensland gold deposits were exceedingly rich, averaging 1 oz/ton in many deposits. The characteristic elements concentrated with gold in the deposits related to the Paleozoic orogenies in Queensland and New South Wales are Cu, Ag, Zn, Cd, B, Pb, As, Sb, Bi and Te.

In New Zealand there are a number of gold districts associated with Paleozoic orogenies and in places with younger (Jurassic) granites – those along or near the west coast of South Island in early Paleozoic rocks, including the Gold Blocks, Aorere, Mount Arthur, Mount Owen, Wangapeka and Preservation Inlet districts; and those in the Marlborough and Alpine schists and in the Otago schists near the southeast end of South Island (Williams, 1974). The Otago schists, shales and greywackes are thought to be at least partly of Paleozoic age by some and of Jura-Triassic age by others. The deposits in these rocks are mainly quartz-pyrite lodes and veins at Bendigo, Macetown, Glenorchy, Skippers, Carrik and Macraes. The deposits at Reefton and Lyell are in the Greenland and Waiuta groups, both consisting of sequences of greywackes, slates and phyllites. These deposits are mainly gold-quartz lodes in shears and faults. The age of both the host rocks and deposits is uncertain. They may be Paleozoic although some have considered them to be Precambrian (Proterozoic) in age (Williams, 1974).

In the Paleozoic gold districts of South Island, New Zealand, the gold deposits belong mainly to the gold-quartz type. The gangue is invariably quartz with pyrite, arsenopyrite, tetrahedrite, stibnite, chalcopyrite, galena, sphalerite, pyrrhotite and abundant scheelite in places. The gold is mainly free, and in most deposits the Au/Ag ratio is greater than 8. The characteristic elements associated with gold in the Paleozoic gold districts of South Island are Cu, Ag, Zn, Cd, Pb, As, Sb and W.

Elsewhere in Australasia there are a few small primary deposits of the gold-quartz type that may be related to Paleozoic orogenies, although some investigators consider them to be of Precambrian or Mesozoic age. These deposits occur in Borneo and New Guinea and as far as is known they are not being worked (International Geological Congress, 1930; Emmons, 1937).

Gold placers derived mainly from Paleozoic lodes, were formerly of considerable importance in Eastern Australia in Queensland, Victoria, New South Wales and Tasmania; in New Zealand, and in parts of Borneo and New Guinea. Some are still worked in a small way. Many of these placers are fossil and are of Tertiary age; others are of Quaternary (Recent) age.

Mesozoic

The Mesozoic is that era of geologic time between the Paleozoic and Cenozoic eras and comprises rocks belonging to the Triassic, Jurassic and Cretaceous systems. The orogenic history, and consequently the metallogeny, of the era is complex (Fig. 6).

Mesozoic rocks are confined mainly to the Western Cordillera and Arctic Islands of North America. A few Triassic rocks, including volcanics and sediments, are known along the eastern seaboard of the continent and these are flexed and faulted in places (Palisade disturbance). There are no known gold deposits in the eastern Mesozoic rocks nor in those of the Arctic Islands.

Two major orogenies are manifest in the Cordilleran region, the late Jurassic–early Cretaceous Nevadan (Columbian) and the late Cretaceous–early Tertiary Laramide. The effects of the former, together with earlier, local, Mesozoic orogenies are most pronounced in the western part of the continent whereas those of the latter are more evident along the mountain front. The rocks deformed during these orogenies range in age from Precambrian to Tertiary, but the mineralization is mainly late Jurassic to early Tertiary.

Gold deposits related to the Mesozoic orogenies of the Western Cordillera of North America are widespread from Alaska to Central America. Most belong to the gold-quartz type, but there are also numerous gold-bearing skarn-type deposits, and a veritable host of gold- and silver-rich polymetallic deposits. Placers of Cenozoic (Tertiary and Quaternary) age derived mainly from deposits related to the Mesozoic orogenies were formerly important in the western United States – mainly in California, in British Columbia, in Yukon and in Alaska. Only a few of the hypogene deposits can be mentioned here.

Many of the great gold deposits of the western United States, Canada and Alaska are related to Mesozoic orogenies. Here belong the extensive gold-quartz deposits of California and southwestern Oregon, including the Mother Lode, Grass Valley and Alleghany districts, numerous gold-quartz deposits in Washington, Idaho and other western states, the gold-quartz veins of the Zeballos, Tulsequah, Stewart, Hazelton, Nelson-Ymir-Salmo, Bridge River, Cariboo (Barkerville), Atlin and other districts in British Columbia, gold-quartz veins in Yukon, and gold-quartz veins and lodes in Alaska, particularly at Juneau, Fairbanks and in nearby areas. The host rocks of these gold deposits are extremely varied comprising slates, greywackes, quartzites, argillites, schists, various volcanic rocks, serpentinites and granitic rocks, ranging in age from Precambrian to Cretaceous, and younger in places. In all of the deposits the gangue is quartz with minor carbonates, often ankerite. The metallic minerals are pyrite, arsenopyrite, pyrrhotite, chalcopyrite, galena, sphalerite, tetrahedrite, stibnite and molybdenite. Scheelite is common in some veins. The gold is free in most of the deposits, but in some it is intimately associated with pyrite and/or arsenopyrite. In a few deposits gold-silver tellurides are reported. The Au/Ag ratio of the deposits is variable; in some the ratio is as high as 9, in others as low as 5. The grade averages about 0.5 oz/ton Au, lower in some and higher in others. The characteristic elements concentrated in addition to gold include Cu, Ag, Zn, Cd, B, Pb, As, Sb, Bi, Se, Te, Mo and W.

In addition to the typical gold-quartz veins related to Mesozoic orogenies in the Western Cordillera there are also a few skarn-type gold deposits of the same period, exemplified by the Nickel Plate and French mines at Hedley, British Columbia. Considerable amounts of gold are also won as a byproduct of a variety of Mesozoic polymetallic deposits, mainly those mined for copper, silver, lead and zinc.

Gold deposits associated with Mesozoic orogenies in the Cordillera of South America are minor and of little commercial importance compared with those of Tertiary age. Some gold-quartz veins and impregnation zones in Chile and neighbouring Argentina are thought to be related to granites and diorites of late Cretaceous and early Tertiary age. More probably the granitic rocks are entirely Tertiary according to some geologists. In Chile the auriferous deposits related to intrusions of Late Jurassic to Late Cretaceous age are mainly veins and breccia pipes (Ruiz and Ericksen, 1962). The veins comprise gold-pyrite types containing quartz, pyrite and chalcopyrite; they are low grade except in the oxidized zones. Another vein type is marked by the presence of specularite (hematite), magnetite and chalcopyrite; they are medium to high grade deposits. The pipes are circular or lenticular breccia bodies cemented by quartz and coarse-grained tourmaline. They are developed in granitic rocks of various types and grade into or are associated with chalcopyrite-tourmaline pipes. Much of the gold occurs as fine blebs in the chalcopyrite of these deposits.

In Mesozoic time extensive diastrophism and igneous activity did not take place in Africa and Europe, and no gold deposits of definite Mesozoic age are known in these continents. In western Asia the effects of Mesozoic orogeny and igneous activity are confined mainly to the Caucasus, and particularly to the Lesser Caucasus where gold-quartz deposits in ophiolites and other rocks are developed such as at Zodsk (Konstantinov and Grushin, 1972; Borodaevskaya and Rozhkov, 1974). A number of auriferous polymetallic deposits are also worked in the Lesser Caucasus. Some of the gold deposits cut rocks of Upper Cretaceous age and hence may actually be of Tertiary age. In eastern Asia a great belt of Mesozoic and older rocks are folded, faulted, granitized and intruded by a variety of granitic rocks from southwest Borneo, through the Malayan peninsula, across China, and into the far eastern part of U.S.S.R. The Verkhoyansk range and the regions flanking the Kolyma massif (Precambrian and Paleozoic) and stretching to Bering Strait reflect this orogeny as do also the Sikote-Alin range in U.S.S.R., parts of South Korea and the southern part of Honshu in Japan. This orogenic epoch, commonly referred to as Yen Shanian, is mainly of late Cretaceous age, but its effects are also manifest in early Tertiary rocks in some districts.

A number of gold-quartz veins and lodes are known in Mesozoic rocks in southwest Borneo, Malaya, Thailand, Cambodia, Laos and Vietnam, but these are mainly small and are not worked. Derived placers still provide a little gold in places. In many places the primary lode gold and vein deposits thought to be of Mesozoic age in these countries may actually be late Cretaceous–Tertiary in age. In China gold deposits, mainly of the gold-quartz type, related to post-Jurassic orogenic events, have been productive mainly in Szechwan Province. In the eastern Transbaikal region and in the far eastern U.S.S.R., in rocks affected by Mesozoic diatrophism and granitic intrusion, there are a large number of productive gold deposits, mainly of the gold-quartz type, but also including gold-bearing pyritized, silicified zones, skarns and gold-bearing dykes, in the Yana-Kolyma folded belt, in the Okhotsk Mesozoic folded regions, in the Chukotka region, on the north slope of the Aldan Arch, in the Sikhote Alin range and elsewhere (Kunaev, 1963; Ditmar, 1966; Sidorov, 1966; Konstantinov *et al.*, 1967; Apel'tsin *et al.*, 1968; Gorzhevskii *et al.*, 1968; Shilo *et al.*, 1969; Gamyanin and Solov'ev, 1969; Kogen, 1969; Obolenskii and Obolenskaya, 1972; Perelygina, 1973; Berger and Kuz'min, 1975; and others). According to Zagruzina (1972) the sequence of gold mineralization, as determined by absolute age dating, in the northeastern U.S.S.R. from the Upper Jurassic to the Paleogene was as follows: early (mainly Mesozoic) gold-quartz veins, stockworks, silicified zones, etc.; gold-rare metals deposits; and late (mainly Paleogene) gold-silver deposits. Large eluvial, eluvial-talus, alluvial and beach placers, which have derived much of their gold from the hypogene Mesozoic deposits, are also worked in all of these areas.

A general review of the nature of the gold-quartz and other gold-bearing deposits in the Mesozoic and older rocks of Asia and related to late Mesozoic diastrophism and associated granitic activity indicates that quartz is the principal gangue with carbonates and minor barite in some districts. The metallic minerals include pyrite, pyrrhotite, arsenopyrite, galena, sphalerite, chalcopyrite and tetrahedrite. A number of deposits contain stibnite, various sulphosalts often silver-bearing, molybdenite, bismuthinite, scheelite and rarely cassiterite. The gold is generally free, but some is intimately associated with arsenopyrite and pyrite or with stibnite and sulphosalts in some deposits. Tellurides occur in some deposits (Darasun). Wall-rock alteration effects (beresitization, chloritization, tourmalinization, carbonatization, etc.) are marked in many of the deposits. Mineral zoning and pulsation are also common in some of the deposits. Many of the deposits are deeply oxidized and enriched (e.g., the karstified Kuranakh deposits) (*see* Chapter IV). The Au/Ag ratio commonly ranges from 7 to 9, but in some deposits the ratio is 1 or less. Deposits with low Au/Ag ratios generally belong to late orogenic events that span Cretaceous–early Tertiary time.

Most seem to belong to the Tertiary suite of gold deposits mentioned in the next section. The characteristic elements concentrated with gold in the Mesozoic orogenic belts of Asia include: Cu, Ag, (Ba), Zn, Cd, (Hg), B, (Sn), Pb, As, Sb, (Bi), Se, Te, Mo, W, F, (Co), (Ni) and (U). Those noted in parentheses are occasional or rare.

Gold deposits related to Mesozoic orogeny and igneous activity appear to be rare in Australasia. In the Tasman geosynclinal zone in southeastern Queensland, Australia, the Au, Cu, Sb and Hg mineralization near Maryborough is probably of Upper Cretaceous age, related to the Maryborough orogeny. The gold deposits occur at North Arm and are apparently associated with Late Cretaceous intrusions of granite, syenite and diorite (Jones, 1947; Hills, 1947). Warren (1972) records that plugs and bosses of granite were intruded during Cretaceous time in places in northeastern Australia. They have associated small gold lodes west of Mackay. Small gold lodes also occur in Cretaceous peralkaline plugs at Mount Dromedary south of Sydney and at Cygnet, south of Hobart, Tasmania.

Cenozoic

The Cenozoic is the latest of the four periods of geologic time, extending from the close of the Mesozoic era to and including the present. The Cenozoic era includes the rocks formed during the Tertiary (Paleogene and Neogene) and Quaternary periods.

The Cenozoic represents one of the major periods of gold concentration in the geological history of the earth (Fig. 7). The Tertiary (Paleocene to Pliocene) period is notable for the extensive deposition of hypogene gold deposits in many parts of the world, and both the Tertiary and Quaternary represent two periods when many of the great gold placers of the world were formed. Even today in the Recent (Holocene) epoch hypogene gold deposits are still forming (in New Zealand and elsewhere), and gold is being concentrated in stream, river and other types of sediments. Finally, the oxidation of gold deposits during Tertiary and Quaternary time has led to secondary enrichment of gold (and silver) in many deposits throughout the world.

In the Cordillera of North America the early Tertiary period was marked by the extensive injection of sills and stocks of monzonite, granodiorite and their related porphyries into older rocks ranging in age from Precambrian to Cretaceous. This period was accompanied, or followed in the early and late Tertiary, by marked orogenic disturbances, which resulted in uplift, warping and faulting of large regions of the Cordillera, and the outpouring of andesitic and rhyolitic lavas on a vast scale. While this general scheme of events may hold in some districts, when the details of the geological features in particular areas are examined there are many complexities. For instance it seems that in some areas of the eastern parts of the Cordillera the early Tertiary magmatic events are simply a continuation or an eastward extension of those that affected Cretaceous and older rocks in the western parts of the Cordillera. In addition, the sequence of sedimentation, volcanic activity and magmatic activity during the Tertiary is extremely complex and not readily correlated from district to district. Finally, in many districts it is difficult to sort out mineral deposits which belong to Tertiary orogenic events from those that were formed during the Mesozoic, Paleozoic or Precambrian. Increasing use of radioactive age-dating methods may resolve some of these difficulties in the future.

The above complexities notwithstanding, it can be said that Tertiary orogenic events, manifest by widescale diastrophism, volcanism and intrusion by granitic rocks and porphyries, can be traced from Alaska, through British Columbia, where they are less pronounced, southward with increasing intensity through the western United States into Mexico and Central America where they attain their greatest development. Gold deposits of great importance are related to these Tertiary events particularly in the western United States, Mexico and Central America. The gold-bearing pyrrhotite-chalcopyrite-pyrite ores of Rossland, and a few other gold-bearing deposits in the Boundary district of British Columbia, are now considered to be of early Tertiary age (Fyles *et al.*, 1973), but Thorpe and Little (1973) caution against accepting this age for the mineralization. Scattered deposits in Alaska (Unalaska Island, Unga Island) are probably also of Tertiary age. The Dusty Mac gold-silver deposit in silicified Eocene volcanic rocks near Okanagan Falls, British Columbia is Cenozoic in age (Church, 1973). It is described in more detail subsequently. These seem to be the only gold deposits of definite Tertiary age in British Columbia and Alaska, but there are probably others which may prove to be of this age. The Mount Nansen gold-silver deposit in the Yukon, described by Saager and Bianconi (1971), is most probably of late Cretaceous–early Tertiary age. This deposit is a system of narrow, steeply dipping veins in rocks ranging in age from Precambrian to Tertiary. The mineralization consists essentially of quartz veins with pyrite, arsenopyrite, sphalerite, galena, freibergite and native gold. The Au/Ag ratio of the deposit is low, averaging about 0.03; the fineness of the native gold is about 800.

The characteristic hypogene gold deposits of the Tertiary in western North America are predominantly gold-quartz and allied types often with an abundance of silver and base metal sulphides and sulphosalts. Here belong the deposits of Republic in Washington; Tonopah, Rawhide, Goldfield, Comstock Lode, Tuscarora and Jarbidge in Nevada; Bodie in California; the Black Mountains in Arizona; De Lamar in Idaho; the San Juan region (Telluride, Ouray, Silverton, Lake City, Rico, Needle Mountains, La Plata and Creede) and Cripple Creek in Colorado; Pachuca, El Oro and Guanajuato (Veta Madre) in Mexico; and a number of deposits in Central America. The disseminated Carlin, Cortez, Getchell and Gold Acres deposits in Nevada also belong in the listing, according to the latest dating investigations.

The host rocks of the Tertiary deposits of the Cordillera of North America are varied and include andesites, trachytes, rhyolites and various porphyries of Tertiary age; Tertiary shales, limestones and sandstones; and older Mesozoic, Paleozoic and Precambrian rocks of sedimentary, extrusive volcanic and intrusive igneous origin. The alteration processes are, likewise, varied depending on the rock types – characteristic, however, is the marked propylitization (chloritization, carbonatization and pyritization) and sericitization manifest in the Tertiary andesites. In other rocks silicification, pyritization, sercitization and alunitization are common. The gangue of the veins is invariably quartz, often chalcedonic, banded or crustified, with abundant calcite in some places, rhodochrosite in others and rhodonite, adularia, fluorite and barite in a few deposits. The metallic minerals include pyrite, chalcopyrite, galena, sphalerite, argentite, polybasite, pyrargyrite, proustite, tetrahedrite, pearceite, silver selenides (naummanite), stibnite, molybdenite, bismuthinite and wolframite. Arsenopyrite and pyrrhotite are relatively uncommon. The gold is generally free, although some is intimately associated with the sulphosalts. Much of the gold is extremely fine grained giving a yellow hue to the quartz in some deposits. Tellurides are common as at Cripple Creek in Colorado. The Au/Ag ratio is relatively high in some deposits ranging from 5 to 40 with an average of about 10 at Cripple Creek; elsewhere and more generally the ratio is 1:1 or as low as 1:250 (Tonopah, Pachuca, etc.).

The disseminated deposits of Carlin, Cortez, Getchell and Gold Acres in Nevada are described in more detail in a later section. Briefly they are bedded and irregular disseminated deposits in altered and mineralized calcareous siltstones and limestone or in brecciated and fractured zones in these rocks. The mineral assemblage is pyrite, arsenopyrite, quartz, realgar, stibnite, cinnabar, sphalerite, galena and gold.

The elements associated with gold in the Tertiary deposits of the Cordillera of North America are variable – generally they include: Cu, Ag, Ba, Zn, Cd, Hg, (B), Pb, As, Sb, Bi, Se, Te, Mo, W, F, Mn, (Co), (Ni) and (U). Those in parentheses are rare or occasional.

The Tertiary rocks and the orogenic events, which have affected them and the older rocks of the Cordillera of South America, are closely analagous to those described for North America. The Tertiary in South America was a time of intensive mineralization, particularly for copper, silver and tin. Gold accompanied this mineralization over a widespread area, but most of the strictly gold deposits are small and low grade with the exception of those in Colombia and a few in Chile and Peru.

Most of the Colombian gold deposits belong to the gold-quartz type and are found in fractures, faults and stockworks that cut Tertiary and older rocks of both sedimentary and volcanic derivation. The most productive gold deposits lie in the Central Cordillera mainly in the departments of Antioquia, Caldas, Tolima and Chocó. The gangue is invariably quartz with carbonates, and the metallic minerals are mainly pyrite, arsenopyrite, pyrrhotite, galena, sphalerite, argentite, chalcopyrite, bournonite, jamesonite, tetrahedrite, stibnite, stephanite, pyrargyrite and cinnabar. The gold is generally free, but in some deposits it is intimately associated with arsenopyrite and various sulphosalts. Tellurides are reported in some of the deposits. The Au/Ag ratio exceeds 1 in some deposits; in others it is much less than 1. Placers derived from the hypogene Tertiary deposits were extensively worked in some of the departments. Some of these contained relatively large amounts of platinum minerals. The elements associated with gold in the hypogene Tertiary deposits of Colombia and other countries in South America include: Cu, Ag, Ba, Zn, Cd, Hg, (B), Pb, As, Sb, (Bi), Se, Te, (Mo), (W), (F), (Co) and (Ni). Those in parentheses occur only in some deposits as far as the writer can ascertain. Boron is especially abundant in some of the quartz-chalcopyrite-tourmaline-breccia pipes in granitic rocks in Chile, as at the El Chivato deposit (Ruiz and Ericksen, 1962).

Tertiary (Alpine) orogenic events affected parts of the North African coastal region and certain zones in Ethiopia, Uganda, Kenya, Tanganyika and Mozambique included in the Great Rift Valley system of Africa. There are no gold deposits of importance associated with these orogenic events in North Africa, although gold occurs in small quantities in some of the copper, lead-zinc, antimony and mercury deposits in Morocco, Algeria and Tunisia. Post-Triassic (probably Tertiary) gold-quartz veins and stockworks occur in Malagasy (Madagascar) near Andavakorera in a hot spring area. The mineralization of these deposits is essentially quartz, dolomite, calcite, barite, chalcopyrite, galena, sphalerite, pyrite, marcasite and native gold. The fineness of the gold averages about 700. These deposits appear to be the only manifestation of gold mineralization associated with Tertiary orogenic events in southern Africa.

Tertiary rocks are widespread in Europe and comprise extensive thicknesses of sediments and volcanics, particularly in a belt that flanks the Mediterranean Sea (the Tethys Geosyncline) and extend from Portugal and Spain to Turkey in Asia and eastward through the Black Sea region into the Caucasus. These rocks were profoundly affected during the great Alpine orogeny of the Tertiary, which extended into the Quaternary. Parts of the belt are still tectonically active. Mineralization of various types occurs all along this belt but only in four areas – in Spain (Rodalquilar goldfield), in Romania (Transylvania), in eastern Czechoslovakia and adjacent Ukrainian S.R.R. and in a few places in the Caucasus – were gold deposits of economic significance deposited. The Spanish, Romanian and Czechoslovakian deposits are typical and are briefly described.

The Rodalquilar goldfield is located in the Tertiary volcanic complex of the Iberian Peninsula, east of Almeria in southeastern Spain. The deposits are quartz veins, stockworks, breccia fillings and silicified bodies mainly in dacites, andesites, rhyolites and pyroclastics. Near the deposits and in places regionally, the volcanic rocks are extensively propylitized and argillitized, the principal alteration minerals being quartz, alunite, pyrite, illite, kaolinite and chlorite. Near the veins the associated alteration is quartz-alunite-pyrite-illite-kaolinite, and this grades outward into chloritic rocks. The mineralization of the deposits is essentially crystalline and colloform quartz, pyrite, alunite, jarosite, gold tellurides and a variety of sulphides including marcasite, pyrrhotite, covellite and chalcocite. At a depth of 200 m the gold mineralization is said to change sharply to a zone of complex sulphides. The age of the mineralization is Tortonian-Andalucian (Miocene). Details of the deposits are given by Friedrich (1960) and Vivaldi *et al.* (1971).

In Romania, particularly in the Apuseni Mountains (Brád) gold belt, the basement rocks are folded Mesozoic limestones, shales, conglomerates and sandstones on which are laid Tertiary sediments and tuffs, now folded. Intruding and covering the Tertiary sediments and tuffs are rhyolites, dacites, andesites and basalts. Volcanic necks composed of rhyolite, andesite, dacite and breccias of these rocks invade the Tertiary sediments and tuffs at many points. Faults, fractures and brecciated zones of Tertiary age cut the various Tertiary volcanic and sedimentary rocks, and in places these are filled with quartz accompanied by calcite, rhodochrosite and barite. The metallic minerals are mainly pyrite, arsenopyrite, sphalerite, stibnite, tetrahedrite, bournonite, galena, argentite, pyrargyrite, stephanite, cinnabar and gold. Most of the gold is free and tellurides occur in some of the deposits. In the typical gold deposits the Au/Ag ratio ranges from 1:2 to 1:4; silver-rich deposits have ratios in the range 1:100 to 1:200. The wall-rock alteration includes extensive propylitization, kaolinization, sericitization and silicification. Many of the veins occur within the confines of the volcanic necks, lying parallel to the long axes of the necks; others rim the necks. There are similar veins in or associated with Tertiary rhyolite, andesite and dacite plugs in the Baia Mare district some 120 mi north Brád. These veins show a marked hypogene zoning from the surface downward as follows: a zone rich in gold-bearing sulphides, argentiferous sulphosalts and silver; a zone rich in argentiferous galena and sulphosalts; a zone rich in sphalerite; a zone rich in copper sulphides; and a zone rich in pyrrhotite. There is considerable similarity both in the structural setting and mineralization of the veins in the Brád and Baia Mare gold belts to those in the Cripple Creek volcanic centre in Colorado. The elements associated with gold in the Transylvanian deposits include Cu, Ag, Ba, Zn, Cd, Hg, (B), Pb, As, Sb, (Bi), Mn, Se and Te. Those in parentheses occur only in some deposits as far as the writer can ascertain.

In the Western Carpathians of Czechoslovakia is situated Banskä Stiavnica, one of the oldest mining towns in Europe. Near this town a number of gold-silver deposits have been worked in the Kremnicko-Štiavnické Rudohorie Mountains since the 15th century, and it is said before this by the Celts. The area is underlain by Paleozoic schists, conglomerates and sandstones and Triassic shales, quartzites, limestones and dolomites, intruded by granodiorite, quartz diorite and dacite (Mesozoic and Tertiary?). All of these rocks are overlain and intruded by Tertiary andesites. The veins developed in faults and fractures, cross all of the rocks of the district and are probably Miocene in age or younger. The mineralization is of a polymetallic type, lead and zinc prevailing over copper. In the Štiavnica district the gangue material consists essentially of quartz, in places with hematite (the so-called cinopel). Other gangue minerals, present usually in small amounts, are carbonates, rhodonite and barite. The upper portions of the veins were rich in silver and gold. In the Hodruša district the gangue is mainly quartz and carbonate with negligible amounts of pyrite and the base metal sulphides. The wall-rock alteration consists of extensive propylitization, some of it regional in character, pyritization, sericitization and carbonitization. The metallic minerals include pyrite, chalcopyrite, galena, sphalerite, tetrahedrite, stephanite, argentite and polybasite. Some of the veins, especially in the Štiavnica district, show a vertical zonation from the surface downward as follows: a zone rich in gold and silver (secondary?); a zone rich in galena and sphalerite with abundant rhodonite; a zone rich in sphalerite and galena with considerable chalcopyrite; and a zone rich in chalcopyrite and pyrite. Scheelite appears in the chalcopyrite zone and increases in content with depth. The ores are generally low in gold, the ratio Au/Ag being about 1:45 according to old reports. A modern description of the veins is given by Koděra (1963). Somewhat similar gold-bearing deposits occur in western Ukrainian S.S.R. in the Beregovo mining district (Boev, 1971). The Begansk deposit is a quartz-alunite-barite-polymetallic lode, and the Beregova deposit is characterized by the presence of quartz, alunite, gold and various polymetallic sulphides. The host rocks are Tertiary volcanics and sediments mainly of Miocene age. The elements concentrated with gold in the Carpathian deposits are Cu, Ag, Ba, Zn, Cd, (Hg?), Pb, As, Sb, Se, Mn and W.

The southern and eastern parts of Asia are marked by two great Tertiary orogenic belts that seemingly coalesce in the East Indies. The southern belt, usually designated as the Alpine Himalayan belt, passes through Turkey, Iran, Afghanistan, the Himalayan region and thence into Burma. Parts of Thailand seem also to have been affected by Tertiary and Quaternary orogenic and magmatic events since numerous hot springs are still active in places. The eastern belt includes the mountainous volcanic islands of Sumatra, Java, Borneo and Sarawak, New Guinea, the island arcs of the Celebes, the Philippines, Taiwan, Ryukyu Islands, Japan, Sakhalin Island, the Kuriles and Kamchatka and the region to the northeast. Bordering the sea of Okhotsk and extending into the region of northeast Chukotka there is another volcanic fold belt, designated by some Russian writers as the East Asiatic tectonic-magmatic belt, that was active in the Tertiary and is still tectonically active in places. These great belts of Tertiary and Quaternary orogeny affect rocks of many ages, ranging in some places from Precambrian to Recent. The eastern belt in particular was the site of great volcanic activity in the Tertiary and is still the site of such activity in places today.

The Alpine-Himalayan orogenic belt contains gold deposits related to Tertiary orogenic events, but most of the hypogene veins and lodes mined essentially for gold appear to have been small. The Anatolia goldfield in Turkey extends south from the Dardanelles (and the site of ancient Troy) to the valley of the present Gediz, the river a tributary of which was known in antiquity as the Pactolus and from which the treasure of Croesus is said to have come. Still farther south in the Boz Dagh (Mount Tmolos) area and in southern Anatolia in the Bolkar-Dag (Taurus Mountains), Tertiary hypogene gold deposits are also known. Most of the gold in the Anatolia goldfield was won from Tertiary and Quaternary placers or from the oxidized zones of gold-quartz and polymetallic deposits. These deposits occur in mica schists, liparites, augite andesites and basalts of both Tertiary and older age. The veins and lodes contain essentially quartz, pyrite, argentiferous galena, sphalerite and chalcopyrite. The Au/Ag ratio appears to range from 1:10 to 1:5.

The Pontic goldfield, on the south shore of the Black Sea in the Trabzon (Izpir) district of Turkey, is in an area of Tertiary volcanics and sediments. One theory has it that this is the field in which Jason sought the 'Golden Fleece' since the ancient miners there used sheep fleeces to catch the gold during placer operations. Yet another theory holds that this is the site of the golden land of Havilah mentioned in Genesis 2(10–12) (*see also* Chapter I). Few hypogene gold deposits actually occur in this area. Most of the gold appears to have been derived from the oxidation zones of massive and disseminated Pb-Zn-Cu sulphide bodies.

Descriptions of the gold deposits and occurrences in Turkey are given by Karajian (1920), Bayramgil (1945), Nahai (1958), Ryan (1960) and Gümüs (1970).

Gold-bearing deposits occur on the eastern extension of the Turkish Pontic belt in Armenian S.S.R., east of Yereven and in other parts of the Trans-Caucasus (Konstantinov, 1973*a*, 1974; Borodaevskaya and Rozhkov, 1974). There, the deposits are apparently of Oligocene to Early Miocene age and occur in intrusive rocks (gabbro, diorite, granodiorite) and effusive-sedimentary rocks (rhyolites, quartz albitophyres, andesite porphyries, tuffs, etc.). The orebodies are gold-quartz-sulphide zones, impregnations and veins (Zod, Tutkun, Lalikh, etc.), and fracture-filled veins (Megradzor, Armanis, Agduzdag) in great fault zones. The mineralization is essentially quartz, carbonates, pyrite, arsenopyrite, chalcopyrite, tetrahedrite, various other sulphosalts, stibnite, gold, tellurides and a host of other minerals in small amounts. Listwänitization of gabbros and serpentinites, beresitization of rhyolites and silicification, chloritization, pyritization and carbonitization of various other rocks constitute the principal wall-rock alteration effects. In Iran there are also gold-quartz veins and polymetallic deposits that are mainly of Tertiary age (Wilson, 1948; Bariand and Pelissier, 1972).

In Afghanistan gold-quartz lodes, probably of Tertiary age, were exploited near Kandahar, and a number of gold placers have been worked in the northeast part of the country. The gold in the placers is evidently largely derived from extensive, lean gold-bearing conglomerates derived from the erosion of the Pamirs (Levat, 1903).

In Burma, gold-quartz veins mainly in Tertiary andesite near Nankan have been worked in the past. The gangue is quartz with carbonates, pyrite, chalcopyrite, franklinite and tellurides, mainly altaite. The great Bawdwin lead-zinc-silver mine produces a little gold. Placers derived mainly from lean Tertiary deposits occur at various places along the great Irrawaddy River and its tributaries: also along a number of other rivers.

The gold mines in Indonesia (Sumatra, Java, Celebes and Borneo) and Sarawak are essentially similar and can be described in general. All are in Tertiary andesites, dacites, trachytes and rhyolites, Tertiary sedimentary rocks including tuffs, conglomerate, sandstone, limestone and shale, or in older rocks most of which are of Mesozoic or Paleozoic age.

The deposits tend to occur close to the Tertiary andesites and other eruptive rocks. All are essentially gold-quartz veins attended by extensive propylitization of the andesites, often on a regional scale. The gangue is quartz with much calcite, rhodochrosite, rhodonite, adularia and zeolites in places. The metallic minerals are variable amounts of pyrite, arsenopyrite, sphalerite, galena, chalcopyrite, tetrahedrite, argentite, pearceite and polybasite.

Many of the veins are crustified and have abundant cockade structures. Much of the gold is free, but some is intimately associated with the various sulphides. Electrum is common in many of the veins, and gold-silver-tellurides occur in a few. The Au/Ag ratio of the ores range from 1:1 to 1:40 in most deposits. The Radjang Lebong deposits contain considerable amounts of selenium. The deposits at Bau in Sarawak are replacements and disseminations in Upper Jurassic to Lower Cretaceous limestone, sandstone and shale, intruded by Tertiary (?) dykes, stocks and sills of dacite and granodiorite porphyry (Wolfenden, 1965; Pimm, 1967). They are marked by considerable zones of silicification (quartz and calc-silicate minerals) in which variable amounts of pyrite, arsenopyrite, galena, sphalerite, proustite, cinnabar, native arsenic, native antimony, realgar, orpiment, stibnite and jamesonite occur. Most of the free gold is microscopic, and there is seemingly much gold in the lattice of the native arsenic according to the investigations by Lau (1970). Placers derived from the hypogene Tertiary deposits are worked in places in Indonesia (Sigit *et al.,* 1969).

The gold deposits of the Philippines occur mainly in Tertiary rocks in the Baguio, Aroroy, Paracale (Mambulao) and Suyoc districts. The host rocks are mainly andesites and associated sediments intruded by porphyritic dacites and quartz diorites. The deposits are mainly gold-quartz veins and polymetallic deposits in fissures and faults. The gangue is essentially quartz with manganiferous carbonate, anhydrite and calcite. The quartz is frequently opaline. The metallic minerals include pyrite, sphalerite, galena and chalcopyrite. Crocoite ($PbCrO_4$) occurs in some of the veins near Manila. The gold is mainly free. A recent description of the Philippine gold deposits is given by Bryner (1969).

The gold deposits of Taiwan are mainly gold-quartz veins in Tertiary andesites and associated sediments intruded by andesite, dacite and various porphyries. The mineralization is typical of many Tertiary deposits and includes quartz, barite, rhodochrosite, alunite, pyrite, enargite, chalcopyrite, sphalerite, galena and stibnite. Much of the gold is free.

The gold deposits of Japan are mainly of Tertiary (Neogene) age, although some (Omidaui, Asahi and Kabutoyama in southern Honshu) are of Cretaceous age. Those of Neogene age are described by Nishiwaki *et al.* (1971).

The Miocene and Pliocene geology of Japan is characterized by a volcanic and associated sedimentary complex extending from Northern Hokkaido to southern Kyushu, comprising andesites, dacites and rhyolites interbedded with tuffs, breccias and terrestrial and marine shales, limestones, arkose, etc. The andesites are highly propylitized as are also many of the tuffaceous rocks giving rise to the general term 'green tuff' used by many Japanese geologists. This term is somewhat equivalent to 'greenstone' used by Canadian and other geologists for volcanic terranes in Precambrian rocks. Nearly all of the economic gold-silver deposits of Japan occur in these 'green tuff' rocks, as do also many of the massive sulphide deposits called 'kurokô' by the Japanese. The latter deposits also yield considerable amounts of silver and gold.

The principal types of Japanese gold-silver deposits include gold-quartz fissure veins, gold-quartz stockworks and massive gold-quartz stockwork deposits in which the intervening host rock is intensely silicified. The gangue is invariably quartz often with adularia, barite, calcite, rhodochrosite, rhodonite, inesite, johannsenite, ankerite, sericite, kaolinite and other clay minerals. The quartz is commonly chalcedonic with a rhythmic banded crustification of white to grey quartz alternating with grey to black fine-grained sulphides greatly enriched in gold and silver (the 'ginguro' of the Japanese prospectors). The metallic minerals occur in variable amounts and include pyrite, chalcopyrite, sphalerite, galena, arsenopyrite, stibnite, ruby silver, argentite, pearceite, polybasite, stephanite, miargyrite, native silver and tetrahedrite-tennanite. The gold minerals are mainly gold-electrum usually ranging from 10 to 20μ in diameter. Gold-silver tellurides are rare as are also the selenide minerals. In some veins the polybasite and argentite are rich in selenium. Enargite and luzonite occur in some deposits, particularly in the large silicified Kasuga and Akeshi deposits in southern Kyushu. The latter deposit also contains abundant native sulphur. The Au/Ag ratio in some deposits is 1:1 or less, in others 1:10 to 1:40 or more. The elements accompanying gold in the Tertiary deposits of Japan include: Cu, Ag, Ba, Zn, Cd, (Hg), (B), Pb, As, Sb, (Bi), Se, Te, (Mo), (W) and Mn. Those in parentheses are rare or occasional.

The Tertiary terranes and orogenic belts of the far eastern U.S.S.R. including the Kuril Island arc, Sakhalin Island and Kamchatka, and the great volcanic fold belt bordering the Sea of Okhotsk and extending into Chukotka contain a number of hypogene gold deposits similar in many respects to those found in Japan and elsewhere in the eastern Tertiary orogenic belt. Placers derived from these deposits are widespread (Fig. 87). Summary descriptions of the gold-bearing areas and deposits are given by Nikol'skii (1963), Radkevich *et al.* (1965, 1969), Sidorov (1966), Yugai (1967), Aprelkov and Kharchenko (1968), Shilo *et al.* (1969), Rozhkov (1971*b,c,d*), Bolarovich (1972), Zagruzina (1972), Borodaevskaya and Rozhkov (1974) and Roslyakova and Roslyakov (1975).

The gold-bearing deposits of the far eastern U.S.S.R. can be classified into four categories: gold-quartz, gold-rare metal, gold-silver and gold sulphide (Shilo *et al.*, 1969).

The gold-quartz deposits are mainly veins and irregular bodies generally related to folding. They are particularly common in the Mesozoic rocks of the northeastern U.S.S.R. Their mineralization consists essentially of quartz, carbonates, pyrite, arsenopyrite, galena, sphalerite, sulphosalts and native gold. The age of many of these deposits is apparently middle to late Mesozoic (Zagruzina, 1972).

The gold-rare metal deposits are mainly veins and lodes associated with faults and fracture systems and are said to be related mainly to granitoid intrusions of the volcanoplutonic gabbro-andesite-granodiorite clan. The mineralization occurred in at least two stages – first greisenization with the development of wolframite and molybdenite followed by quartz, carbonates, disseminated base metal sulphides, cassiterite (wood tin in places), wolframite, scheelite, bismuth tellurides, gold and gold-silver tellurides. The age of this mineralization is Late Cretaceous–Paleogene.

The gold-silver deposits are veins and stockworks associated mainly with deep faults. Their mineralization comprises essentially quartz, commonly colloform banded, rhythmically crystalline banded, drusy or platy, adularia, rhodonite, rhodochrosite, base metal sulphides, hematite, stibnite, argentite, silver sulphosalts and gold. Some deposits are transitional to the gold-rare metal-polymetallic types of deposits. Propylitization is characteristically developed in the volcanic host rocks of many of the gold-silver deposits. Most of the gold-silver deposits are Late Cretaceous to Paleogene in age.

The gold-sulphide deposits are complex mineralogically, comprising essentially quartz, albite, carbonate, chlorite, hydromica, pyrite, chalcopyrite, galena, sphalerite, tetrahedrite, silver sulphosalts and gold. The sulphides may make up 30 to 40 per cent of the ores. Propylitization of the andesite host rocks of the gold-sulphide deposits is common and widespread. The age of the deposits is apparently Late Cretaceous–Paleogene, mainly the latter.

From the descriptions of various deposits in the far eastern U.S.S.R. it would appear that propylitization is not as common as in other Tertiary deposits, but in some areas of Tertiary andesites and older basic volcanics this type of alteration is well developed. Alunitization is common in some deposits in Kamchatka and elsewhere. Argillization is distinctive in a number of deposits, and hydromicas occur abundantly in many veins. Adularia is a frequent mineral in numerous deposits. Some deposits have an early phase marked by quartz, cassiterite and tourmaline. Bismuth minerals, molybdenite and wolframite are present in many of the deposits but rarely in commercial amounts. Tellurides are common in some veins, selenides in others. Zeolites occur in places and manganese minerals (rhodonite, rhodochrosite) are a general feature of many of the deposits. The gold is commonly finely divided and usually low in fineness (<500–800). The elements accompanying gold in the Tertiary deposits of the far eastern U.S.S.R. include Cu, Ag, Ba, Zn, Cd, Hg, B, Pb, Sn, As, Sb, Bi, Se, Te, Mo, W, U and Mn.

Tertiary rocks are relatively widespread in Australasia, particularly in Australia, New Zealand and New Guinea. The Tertiary of Australia is characterized by sandstone, shale, marl, oil shales, clays, lignite, limestone, chert, tuffs and thick basalt flows in some areas. The small gold deposits of the Cygnet area of Tasmania were thought to be of Tertiary age (Jones, 1947), but are now considered to be Cretaceous (Warren, 1972). With the possible exception of the Cygnet area, hypogene gold deposits of Tertiary age are unknown in Australia, but gold placers, both of eluvial and alluvial character, were formed on a vast scale in Victoria and New South Wales in Tertiary and later times. Many of these were covered with sediments and basalt flows often several hundred feet thick. These are the 'deep leads', which produced much of the gold of Australia before the turn of the century.

The 'auriferous series' of the Coromandel Peninsula of New Zealand in the north part of North Island are composed mainly of Tertiary andesites, dacites, breccias and tuffs, all much propylitized, in places on a regional scale (Williams 1974). These rest on folded and faulted Paleozoic and Mesozoic sediments and volcanics. The deposits are gold-quartz veins that lie chiefly in the Tertiary andesites and other volcanics, but at places some extend into the Mesozoic sediments. The gangue minerals are essentially quartz, calcite, ankerite, adularia, barite, rhodonite and rhodochrosite. The metallic minerals are pyrite, arsenopyrite, chalcopyrite, galena, sphalerite, cinnabar, tetradymite, proustite and argentite. The gold is generally free although in some veins it is not visible and is closely associated with pyrite, arsenopyrite and other sulphides. Most of the native gold is of low fineness, the average being probably about 700 or slightly less; gold-silver tellurides occur in some veins. The Au/Ag ratio in the deposits averages about 1:7. Some of the veins in the Thames and other districts were fabulous bonanzas, averaging thousands of ounces of gold and silver to the ton. The veins were all deeply oxidized. The elements concentrated with gold in the Tertiary deposits of New Zealand include Cu, Ag, Ba, Zn, Cd, Hg, (B), Pb, As, Sb, (Bi), Se, Te, (Mo), (W) and Mn. Those in parentheses are rare or occasional.

Manifestations of gold mineralization still persist in New Zealand along the Taupo Volcanic Zone of North Island

(Weissberg, 1969). This zone comprises a prism of Quaternary and upper Tertiary volcanic rocks striking northeast in a volcanic-tectonic graben. Hot springs predominate along the eastern margin of the volcanic zone at Waimangu, Waiotapu, Ohahi-Broadlands and Rotokawa. The sinters of these springs and the drillhole discharge precipitates contain abundant opaline silica and amorphous sulphides greatly enriched in Fe, As, Sb, Au, Ag, Hg, Tl, Pb, Zn, P and W. The Au and Ag contents range from 1 to 85 and 5 to 500 ppm respectively. The wall-rock alteration of the rhyolites, ignimbrites and associated lacustrine sediments near the thermal springs and their conduits is marked by the presence of adularia, sericite, quartz, montmorillonite, illite, pyrite, calcite and chlorite.

In New Guinea, Papua and New Irian, gold-bearing deposits are known in several areas. Most are of Tertiary age. Those in New Guinea (Morobe Goldfield, Kainantu Goldfields; Porgera gold deposits) are apparently of late Tertiary (3.5 m.y.) age (Page and McDougall, 1972; Rebec *et al., in* Knight, 1975). The deposits occur in a variety of settings, most being in Tertiary volcanics and sediments. Some are quartz lodes and veins in volcanics and sediments and others are quartz stockworks in highly altered porphyry stocks and sills (gold porphyry deposits). The characteristic metallic minerals are pyrite, chalcopyrite, bornite and molybdenite in the auriferous porphyries. In the banded quartz-carbonate (rhodochrosite) veins pyrite, chalcopyrite, galena, silver sulphides and sulphosalts and minor cinnabar occur. The average primary gold content of the lodes in the Morobe goldfield is about 0.5 oz/ton, and the gold-silver ratio probably averages about 0.04. Many of the near surface parts of the veins, vein zones and auriferous stockworks were greatly enriched in both gold and silver. Both eluvial and alluvial placers have been worked all over New Guinea, Papua and New Irian. Those in the Morobe Goldfield have been highly productive (Fisher, 1945).

The Fiji Islands, lying north of New Zealand, are underlain mainly by Tertiary rocks in which the Vatukoula goldfield on the island of Viti Levu is situated. Blatchford (1953), Cohen (1962) and Denholm (1967) describe the ores of this field as quartz veins in fissures cutting basalt, volcanic ashbeds and andesite dykes of Miocene age. The gangue minerals are quartz and calcite with pyrite, sphalerite, chalcopyrite, pyrrhotite, marcasite and tetrahedrite-tennantite. Gold-silver and other tellurides, including krennerite, sylvanite, empressite, petzite, coloradoite, calaverite and native tellurium, are abundant in the ores (Stillwell, 1949; Markham, 1960; Forsythe, 1968). Native gold when present is mainly free, but some occurs in a submicroscopic form intimately associated with pyrite, arsenopyrite and tetrahedrite-tennantite. Similar deposits occur in Vanua Levu at the former Mount Kasi Gold Mine. The gold-silver ratio in the Fijian ores appears to average about 3:1. The submicroscopic 'native gold' is estimated to be 940 fine by Stillwell (1949).

Remarks on the metallogenesis of gold

As we look back through the pages of geological history, spanning some 3 billion years, we see few distinct patterns with respect to the metallogenesis of gold as related to the great orogenic events that have punctuated the history of the earth. We see dimly a possible relation of gold deposits to particular rock types such as volcanics and their associated sediments, and an indistinct pattern in the elemental constituents of gold deposits, not so much with regard to the elements that are present in the deposits but mainly with respect to those that are not present, or occur only in trace amounts.

In discussing the metallogenesis of hypogene gold deposits we must consider three fundamental aspects: (1) the source of the elements in the deposits; (2) the pathways, including conductive structures and permeable rocks, by which the elements in the deposits reached their sites of deposition; and (3) the sites of deposition or traps containing the deposits, including favourable structures and favourable host rocks for replacement or impregnation. The last two aspects require little discussion here, except to say that during orogenesis there are generally sufficient structures formed, and these are usually extensive enough both in their strike and dip dimensions to tap enormous volumes of rock that could have supplied the constituents of the veins and other types of deposits. In addition, in most orogenic districts there are sufficient structural traps and favourable replaceable rocks for the formation of epigenetic gold deposits. The problem therefore, is one mainly of the source of the gold and accompanying elements. Did these elements come from very deep sources, for example the mantle, from magmas which are generated in most orogenic belts or from the piles of volcanic and sedimentary rocks which constitute the zones affected by orogenesis? Some of the answers seem relatively clear in the light of the preceding discussion of gold deposits in the orogenic belts of the world and the geochemical data given in Chapter II.

When we look in detail at the successive orogenies in the geological history of the earth we note that none are devoid of gold deposits. There appear, however, at first glance to be two general maxima in the number of gold deposits of all types (epigenetic, placer, modified placer, etc.) formed – one maxima characterizes Precambrian time and the other Tertiary time. The orogenies of the Paleozoic and Mesozoic have a number of associated significant economic deposits in many parts of the world, but the total number of such deposits in both epochs is far overshadowed by those of the Precambrian and Tertiary. Perhaps this is an allusion – future prospecting and development may bring to light many deposits that are related to the Paleozoic and Mesozoic orogenies. However, the gold deposits of the Witwatersrand are so overwhelming in their size that one cannot but conclude that the Precambrian was the greatest period of formation of gold deposits in the history of the earth. The Tertiary, on the other hand, may be rivalled or superseded by deposits of Paleozoic and Mesozoic age yet to be discovered. Such seems to be the case as the new gold deposits in Paleozoic and Mesozoic terranes are discovered, developed and brought into production in the U.S.S.R. and elsewhere. We are, therefore, probably only justified in concluding that the Precambrian was the greatest period of gold deposition, and that later periods have about equal numbers of gold deposits. But a closer analysis narrows our conclusion still further. The Precambrian spanned an enormous period of time, some 2.5 billion years, nearly four times that of all of the later eras combined. Furthermore, as the geological histories of the shields and other Precambrian areas in the world are carefully documented, it becomes evident that the number of major orogenies in Precambrian time about equal and may exceed those of later time. It will be recalled that there are at least four major orogenies in the Canadian Shield, and perhaps a number of minor orogenies within these major diastrophic manifestations that remain to be worked out. In Canada, gold deposits are associated with three of the main Precambrian orogenies; in other countries a similar pattern is revealed, numerous gold deposits being associated with the orogenic events that closed the Archean as well as with those that occurred in the Proterozoic. The age of the Witwatersrand system, containing the world's largest gold deposits, was at one time thought to be Proterozoic but is now considered to be Archean (2900 m.y.) on the basis of radioactive age determinations. However, the stratigraphic position of the Witwatersrand system *vis-a-vis* Archean-type greenstones and granitic rocks and numerous other features mentioned in a later section of this chapter suggest to the writer that this great auriferous quartz-pebble conglomerate system is of Aphebian (Early Proterozoic) age. If so, the Early Proterozoic was the greatest period of gold deposition in the history of the earth rivalled only by the Archean. The orogenies that followed in Late Proterozoic and the following eras appear to have about equal numbers of gold deposits, at least to a first approximation.

Those who advocate deep sources, such as the mantle, for the gold and its associated elements in epigenetic deposits have relatively few points in their favour. It is conceivable that some sort of ichor may have delivered gold and its associated elements to favourable structures via fault and fracture systems that penetrate deeply into the earth's crust. It is even conceivable that the generation of gold was marked in Archean time because the source (mantle?) was much nearer the contemporaneous surface than at later times during which the crust of the earth gradually thickened. There are, however, a number of facts that seem to contradict the deep source hypothesis. If deep fault and fracture zones were the conduits up which gold and its associated elements migrated one would expect to find a marked distribution of gold deposits along or near these structures. Such is not the case – few gold deposits are actually localized in the great fault and fracture zones of the earth. Most are in or near relatively small and local structures within a geological terrane, a particularly good example being the formation of gold-quartz lenses and veins in dilatant zones on the crests of anticlines in sedimentary rocks (Bendigo type). Many more examples could be cited such as quartz lodes in drag folds in sediments, in local fracture systems in volcanic necks and dykes, and so on. Furthermore, the formation of most gold deposits seems to be keyed to metamorphic, granitization and magmatic events within a particular area and not to great dislocations in the crust. This relationship is clearly shown by many of the gold deposits in the Canadian Shield. In the Yellowknife district, for example, early shear zones and fractures formed essentially in the volcanic (greenstone) belt, and a variety of local dilatant zones restricted mainly to a greywacke-slate suite of sediments, were extensively mineralized with gold and silver during and following metamorphism, granitization and injection of granitic rocks. Later fault and fracture systems, some extending for distances of 50 mi or more are barren even though they contain many large quartz bodies in places. The writer (Boyle, 1961*a*) postulated that the fundamental differences between the two periods of mineralization in the Yellowknife district can be related to metamorphic events. The productive gold deposits were formed while regional metamorphism, granitization and intrusion of granites was operative; when the late fault and fracture systems were mineralized the wave of regional metamorphism, granitization, etc. had long since subsided. This theme will be further developed in the last section of this chapter.

Numerous investigators have related the occurrence of gold deposits in Archean and Tertiary times, as well as those in other periods, to volcanism and associated sedimentation. This correlation is valid for many gold belts in the world, but a direct relationship to magmatism during volcanic periods is improbable on several counts. As shown in Chapter II, basalts, andesites, rhyolites and other magmatic rocks characteristic of volcanic periods are not enriched in gold. On the other hand the sediments associated with volcanic piles frequently show marked enrichments in gold and silver and their associated elements. In the Canadian Shield these features are quite evident when the analyses of the magmatic volcanic rocks, which average 0.007 ppm Au, are compared with those of their associated sediments that may contain up to 0.1 ppm Au or more. (*See also* Table 16 on the content of gold and silver in iron formations.) One can logically conclude from these data that the main enrichment of gold in volcanic piles is in the sediments, not in the basalts, andesites, etc.

The timing of the formation of gold deposits in volcanic terranes is a most important consideration. Throughout the world gold-quartz veins and other types of gold deposits postdate the volcanic events by a period of time. How long is uncertain, but certainly after consolidation of the lavas and sediments and the injection of igneous dykes and stocks, after folding or block-faulting of these rocks and in most areas after extensive fracturing, faulting and shearing, not only of the volcanic rocks and their associated sediments, but also of the granitic stocks, dykes and batholiths that invade them at a late stage in the orogenic cycle. One can only conclude from these features that there is no direct relationship between volcanic magmatism (i.e., outpouring of lavas, injection of dykes, etc.) and the gold deposits in volcanic terranes.

Tertiary epigenetic gold deposits throughout the world exhibit an intimate relationship to volcanic centres often marked by andesite and dacite flows, dykes, stocks, volcanic necks and tuffaceous sediments. At first glance one might conclude that these deposits are directly related to volcanic magmatism, and some investigators have indeed asserted this view. A close examination of the geological data, however, indicates no direct relationship between the formation of the gold deposits and the magmatic events. An indirect connection is, nevertheless, probable as will be shown presently.

We need not repeat the same arguments about the gold content of andesites, etc. and the paragenesis of the veins with respect to consolidation of the rocks, dyke and stock intrusion, and faulting and fracturing. One sees exactly the same phenomena with respect to epigenetic Tertiary gold deposits as that present in older rocks. Tertiary gold deposits postdate all of the magmatic events except the formation of some late postore dykes in places. Most Tertiary gold deposits appear to be related to thermal waters, which pervade the volcanic and sedimentary piles and today in places appear as hot springs, the sinters of which, in New Zealand particularly, contain gold. All of the evidence from isotopic and other studies suggests that these waters are of meteoric or metamorphic origin. They appear to have collected their gold and other associated elements from the rocks through which they pass. The source rocks are, therefore, of considerable importance.

There are few detailed studies on the source rocks that provided the gold in Tertiary terranes. Judging from the relatively low contents of gold in andesites and dacites these rocks would seem to be poor sources for the metal. More probable source rocks would seem to be the tuffs and sediments in the Tertiary terranes. Even more probable source rocks are those older rocks that form the basement on which the Tertiary rocks were laid down. In many areas these are sediments, often of the carbonaceous pyritic variety, which are considerably enriched in gold wherever they occur. During the dying phases of volcanism in Tertiary times these rocks were evidently heated and permeated by meteoric and metamorphic waters, which mobilized the gold and carried it upward to be deposited in available fractures and faults in the overlying Tertiary andesites and other related volcanics. The Tertiary rocks, mainly andesites, are, therefore, not the main source of the gold but rather the chemically reactive receptacle rocks, which provided the necessary dilatant zones and favourable chemical environment for the deposition of auriferous orebodies. These concepts are discussed in more detail in the last section in this chapter on the origin of gold deposits.

Certain metallogenetic facts should be noted with respect to the relationship of epigenetic gold deposits to volcanism. Considering the Canadian Shield it is apparent that those provinces marked by an abundance of Archean greenstone belts are rich in epigenetic gold deposits, e.g., the Superior and Slave provinces. Those provinces containing relatively few greenstone belts of Archean or younger age are poor in economic gold deposits, e.g., the Bear, Churchill, Southern, Grenville and Nain provinces. On a worldwide basis the same features are evident. Precambrian shields marked by extensive greenstone belts are highly auriferous (e.g., Canadian, Indian, Australian, South African–Rhodesian and Guianian–Brazilian), whereas those shields with few greenstone belts are poor in epigenetic gold deposits (e.g., Baltic, Ukranian, Taimyr, Anabar and Aldan). On a more detailed basis greenstone belts that are complex, containing abundant Algoman-type iron-formations, tuffs, sulphidic interflow sediments and discordant (intrusive) porphyry bodies, and exhibiting extensive shearing, carbonatization and well developed metamorphic facies, especially an inner greenschist facies, are rich in economic epigenetic gold deposits; those composed mainly of piles of volcanics, exhibiting only one facies of metamorphism, tend to be relatively barren. Similarly in Tertiary volcanic terranes, and even in those of Paleozoic and Mesozoic age, complexity seems to produce epigenetic gold deposits. Tertiary and older volcanic terranes marked by quartz porphyry and dacitic plugs, widescale faulting and fracturing, and extensive propylitization are auriferous (e.g., western United States, New Zealand, Romania), whereas those piles of Tertiary volcanics that are relatively simple and unaltered are barren (e.g., northern British Columbia, western Scotland, Ireland, Iceland).

Numerous investigators have attempted to relate gold deposits to orogenic magmatic events, involving either granitization followed by intrusion of the mobile material as granitic bodies, or intrusion of granitic bodies derived by differentiation of mantle or lower crustal materials (Hillebrand, 1954). Gold deposits are supposed to represent one of the hydrothermal stages of magmatic differentiation, an hypothesis that is familiar to all. A detailed criticism of this hypothesis is given at the end of this chapter. It is sufficient to state here that some gold-quartz veins and other auriferous deposits exhibit a spatial relationship to intrusive granitic bodies in orogenic zones throughout the world; other gold-quartz veins and gold-bearing deposits show no such relationship. Nearly all types of epigenetic gold deposits, however, are restricted to rocks that exhibit a low to moderate degree of metamorphism (greenschist to amphibolite facies). One does not find epigenetic gold deposits in rocks that do now show the effects of considerable recrystallization and alteration such as regional propylitization. From this fact the logical conclusion seems to follow that epigenetic gold deposits are more closely related to metamorphic than to magmatic phenomena. In the grand scheme of orogenesis the occurrence of epigenetic gold deposits in the vicinity of intrusive granitic rocks is not fortuitous. The reason for this, however, may not be that the granitic bodies provided the gold, but that these bodies are simply one in the series of products of intense metamorphism. These bodies also include the gold deposits, the gold being derived from piles of sedimentary and volcanic rocks and concentrated as a result of granitization and later metamorphic processes that continued long after the emplacement, crystallization and consolidation of batholiths, stocks and dykes of granite, granodiorite, etc. This theme is developed further in the last section of this chapter on the origin of gold deposits.

The distribution of the great gold belts of the world, ranging in age from Precambrian to Cenozoic, are shown on Figures 3, 5, 6 and 7. Any connection between the belts on one continent and those on another is tenuous to say the least. No relationship appears to exist between the Appalachian (Paleozoic) belt and the Caledonian and Hercynian belt in Europe (or North Africa) as far as the writer can ascertain, although apparently such a possibility exists as regards the European belt (Rast and Grant, 1973). The Precambrian belts in eastern South America and those in western Africa, likewise, appear to bear no particular relationship to each other. Hills (1947) has also drawn attention to the absence of any correspondence between the Precambrian belts in India (Kolar) and those in western Australia. Crawford (1970) has, however, attempted to relate these fields by their age relationships, but his argument on this basis is not convincing. The reader is left to decide how all of this negative evidence is to be resolved in the light of the current wide acceptance of the existence of continental drift.

Pereira and Dixon (1964–1965) discuss evolutionary trends in ore deposition and present a curve that purports to show that there has been an exponential decrease in the grade of gold-bearing deposits with time. This is a difficult problem to deal with because of the lack of relevant data. However, from the writer's experience with gold deposits of all ages this curve cannot be correct. One has only to recall the phenomenal gold bonanzas of the Tertiary. Few such high grade gold deposits occur in earlier periods. Even Tertiary polymetallic deposits seem to show a greatly increased gold content, as in Japan and elsewhere. By comparison, polymetallic deposits of Precambrian, Paleozoic and Mesozoic age are in general much less enriched in gold. The quantitative evaluation of evolutionary trends in gold deposition by Travis (1966), likewise, does not support the conclusions of Pereira and Dixon.

Laznicka (1973) discussed the development of nonferrous metal deposits through geological time and concluded that:

> The sequence of depositional ages based on ore deposits presently outcropping on the earth's surface is, from the oldest to the youngest, Cr,Ni-Au-Cu, Zn-Pb, Ag-Sn, W, Sb, Mo-Hg. Although this sequence parallels several evolutionary trends involved in the formation of the earth's crust, it is believed and semiquantitatively demonstrated that depth of denudation rather than evolution is the more important factor; in other words, the conditions of preservation have had greater influence on the age relationships of ore deposits outcropping on the present earth's surface than have the conditions of formation and their progressive evolution in the earth's history.

The vagaries of the Au/Ag ratio in gold-bearing deposits is considered in some detail in a later section. Here we shall mention only generalities. Overall, Precambrian deposits mined essentially for gold show a high Au/Ag ratio generally greater than 1 and averaging about 5. Paleozoic and Mesozoic deposits, likewise, have ratios generally greater than 1 but probably a lower average, about 3.5 according to the writer's data. Tertiary gold deposits commonly have ratios less than 1, averaging about 0.05. These data seem to suggest that with time silver has been precipitated in increasing amounts compared to gold in strictly gold deposits. In polymetallic deposits of practically all ages, however, silver generally always exceeds gold in amount and the Au/Ag ratio is less than 1, averaging about 0.025. These general statements are negated in a number of gold and polymetallic deposits. One need only recall that some orebodies of Precambrian age (e.g., Yellowknife, Red Lake) have Au/Ag ratios equal to or less than 1. Similarly, some highly productive orebodies of Tertiary age (e.g., Cripple Creek, Fiji) have Au/Ag ratios averaging 3 or more.

The elemental associates of gold in its deposits are discussed at length in the next section. As a preamble some significant facts are presented for consideration. Copper, silver and zinc are invariable associates of gold in epigenetic deposits of all ages; lead is relatively rare in Precambrian deposits occurring generally only as trace amounts in deposits of that age. In younger deposits lead is frequently a minor or abundant element. Mercury is relatively rare in most Precambrian deposits occurring mainly as low traces in the ores. The element appears in trace to minor amounts in younger deposits and may be relatively abundant in those of Tertiary age. Barium is usually present as traces in Precambrian deposits but often appears in minor amounts in those of a younger age. Thallium seems to be enriched in deposits younger than Paleozoic. Tin is relatively rare in practically all epigenetic gold deposits except those rich in sulphides or in stanniferous provinces such as the eastern U.S.S.R. Arsenic is an invariable and intimate associate of gold in all types and ages of epigenetic deposits. Antimony is, likewise, a common associate of gold and is found in practically all types and ages of epigenetic deposits. No particular abundance relationships of arsenic in gold-bearing deposits with respect to type or age of epigenetic deposits are evident. Antimony appears in greatest abundance in vein and lode deposits; it is relatively rare in skarn-type and quartz-pebble conglomerate deposits. Bismuth is relatively rare in most Archean deposits and appears to increase in abundance in those of Proterozoic, Paleozoic and Mesozoic age. In Tertiary deposits its abundance is usually low. Niobium and tantalum are generally only present in trace amounts in all types of epigenetic deposits as are also zirconium and hafnium. Selenium is usually present as traces and minor amounts in epigenetic deposits of all types and ages; in some Tertiary deposits the element is greatly enriched. Tellurium is one of the most frequent associates of gold occurring in practically all types of epigenetic deposits. No age relationships are evident. Deposits in or near volcanic rocks appear to contain the most tellurium; those in sedimentary rocks generally contain only small amounts of tellurium, but some deposits in skarns may be enriched in the element. Molybdenum and tungsten are common in most types and practically all ages of epigenetic gold deposits. The abundance of both elements is usually low. Manganese is found in all epigenetic gold-bearing deposits; in those of Tertiary age the element is frequently abundant as witnessed by the presence of rhodochrosite, rhodonite, inesite, etc. in many deposits throughout the world. Cobalt and nickel are rarely found in any abundance in epigenetic gold deposits, but in some places Co-Ni arsenides and other minerals are notable. Platinum metals are infrequent associates of gold except in the quartz-pebble conglomerate deposits (Witwatersrand) and in placers. Thorium and uranium accompany gold in the quartz-pebble conglomerate and in some skarn, vein and stockwork deposits in uraniferous areas. Most gold deposits containing the two radioactive elements are of Precambrian (Lower Proterozoic) age, although some epigenetic deposits of Paleozoic, Mesozoic and especially Tertiary age are uraniferous.

The auriferous quartz-pebble conglomerates and quartzites are characterized by relatively large amounts of iron in the form of pyrite or the oxides, depending on the particular deposits. The content of sulphur varies almost directly with the amount of pyrite in the ores. The trace and minor element suite (Table 35) is of interest in the origin of these enormous deposits, a point that will be elaborated upon in the last part of this chapter. Briefly, a number of deposits exhibit enrichments of U, Th and rare earths in addition to Au and Ag. There are also enhanced contents of the various base metals in some deposits, including Cu, Zn, Pb, Ni and Co. The As content appears to vary with the content of pyrite in most deposits, and in certain of these deposits the content of gold appears to vary directly with the arsenic content. Deposits with abundant pyrite and other sulphides seem to be enriched in Hg. In general the following elements are usually present in low amounts: In, Tl, Sn, Sb, Bi, Nb, Ta, Se, Te, Mo and W. The general low content of tellurium in these gold deposits is rather remarkable. Some reefs in the Rand (e.g., Carbon Leader) are greatly enriched in platinoids, a feature that is unusual for auriferous deposits.

> Gold–Found in nature as the free metal and in tellurides. Very widely distributed and under a great variety of conditions, but almost invariably associated with quartz and pyrite.
>
> –F.W. Clarke, 1924

Associated elements in gold deposits

The elements with which gold is most commonly associated in hypogene and supergene deposits are mainly chalcophile and include S, Se, Te, As, Sb, Bi, Cu, Ag, Zn, Cd, Hg, Sn, Pb, Mo, W, Fe, Pt, Pd, Co and Ni. There are in addition numerous other elemental associates that are of interest. The author has made a laboratory and literature study of the elemental associations of gold in all types of its deposits, the results of which are given in the various tables accompanying this section and in the discussion that follows. Particularly helpful in this study have been the condensed data given by Lincoln (1911*b*), Cooper (1923), Schwartz (1944), Liebenberg (1955), Petrovskaya (1955, 1973), Radtke *et al.* (1972*a*), Feather and Koen (1975), and Marakushev (1977). Some remarks concerning the association of gold with each of the elements of the periodic table follow. Tables 31, 32 and 33 give a synoptic view of the elements associated with gold in the various types of deposits. The zoning relationships of gold and various elements in epigenetic deposits is discussed in the last part of this chapter and shown in Figures 94 and 95.

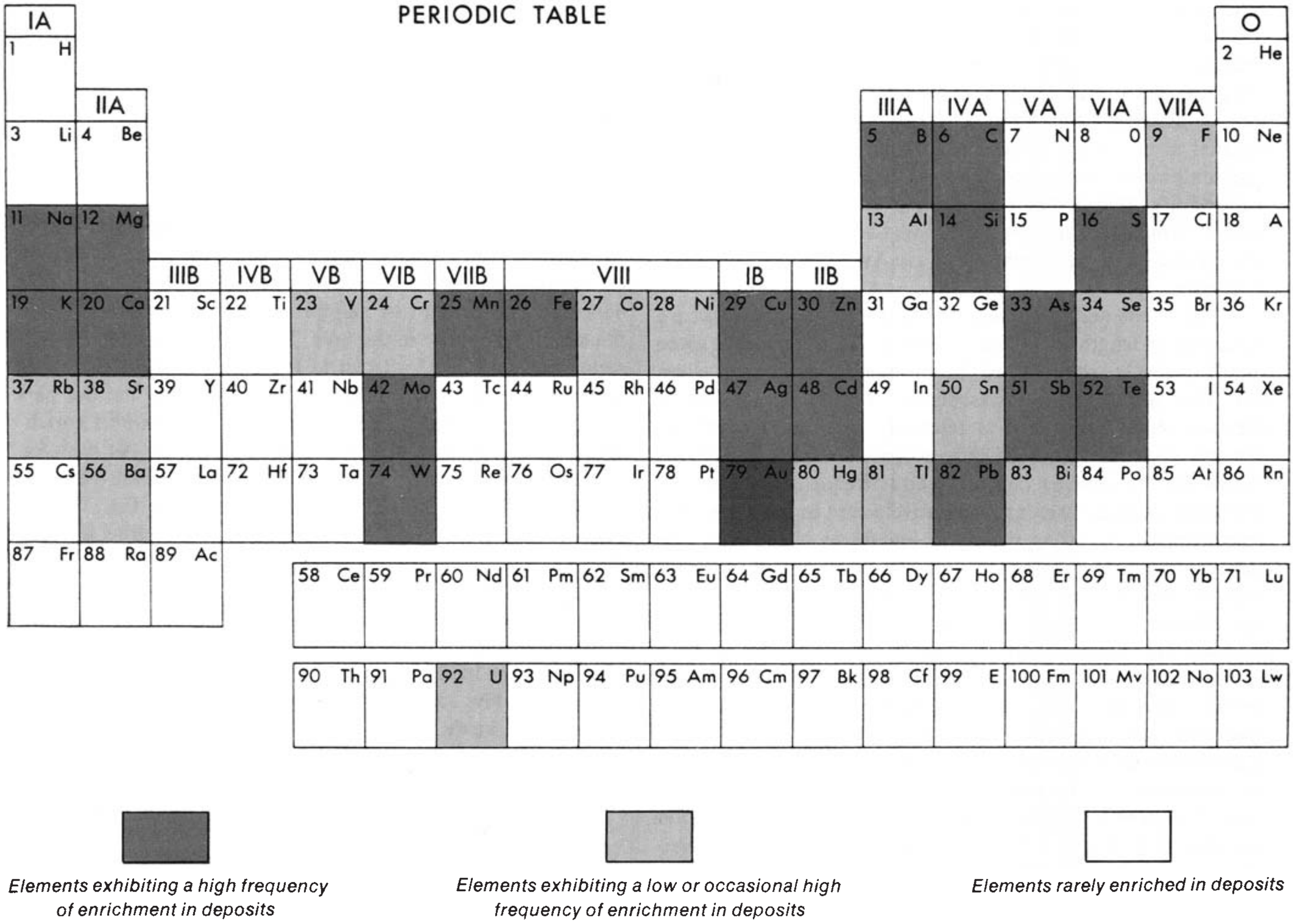
Group IA: H, Li, Na, K, Rb, Cs

Hydrogen requires little comment. The element is an invariable constituent of water and hydroxyl in the various micaceous minerals found in the zones of chloritization, sericitization, etc. associated with many types of epigenetic gold deposits, particularly veins, silicified zones and disseminated deposits. The element is similarily disposed in the sericite, chlorite, chloritoid and pyrophyllite, which forms much of the matrix of the quartz-pebble conglomerate deposits. In the supergene environment hydrogen is a constituent of the water and hydroxyl in hydrous and hydrated oxides of iron, manganese, etc. that invariably occur with gold in the oxidized zones of deposits and in eluvial and alluvial placers.

The role of hydrogen (water) in endogenic wall-rock alteration processes associated with gold deposition is discussed at length in a subsequent section.

Lithium is a typical pegmatite element occurring as a major constituent of minerals such as spodumene, lepidolite, petalite and amblygonite. It is also frequently enriched in certain greisen and micaceous alteration zones associated with tin, tungsten and molybdenum deposits in granitic rocks, gneisses and metasediments. In hypogene gold deposits and their alterations zones lithium is rarely present in amounts greater than 400 ppm. I have not observed lithium minerals in

Table 31. Elements associated with gold in skarn-type, gold-quartz and disseminated deposits. Gangue elements are excluded except if present in abnormally high concentrations.



PERIODIC TABLE

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1 H																	2 He
3 Li	4 Be											5 B ■	6 C ■	7 N	8 O	9 F ▨	10 Ne
11 Na ■	12 Mg ■											13 Al ▨	14 Si ■	15 P	16 S ■	17 Cl	18 A
19 K ■	20 Ca ■	21 Sc	22 Ti	23 V ▨	24 Cr ▨	25 Mn ■	26 Fe ■	27 Co ▨	28 Ni ▨	29 Cu ■	30 Zn ■	31 Ga	32 Ge	33 As ■	34 Se ▨	35 Br	36 Kr
37 Rb ▨	38 Sr ▨	39 Y	40 Zr	41 Nb	42 Mo ■	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag ■	48 Cd ■	49 In	50 Sn ▨	51 Sb ■	52 Te ■	53 I	54 Xe
55 Cs	56 Ba ▨	57 La	72 Hf	73 Ta	74 W ■	75 Re	76 Os	77 Ir	78 Pt	79 Au ■	80 Hg ▨	81 Tl ▨	82 Pb ■	83 Bi ▨	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac															
				58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
				90 Th	91 Pa	92 U ▨	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 E	100 Fm	101 Mv	102 No	103 Lw

■ Elements exhibiting a high frequency of enrichment in deposits

▨ Elements exhibiting a low or occasional high frequency of enrichment in deposits

□ Elements rarely enriched in deposits

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Table 32. Elements associated with gold in quartz-pebble conglomerate deposits. Gangue elements are excluded except if present in abnormally high concentrations. (For key *see* Table 33.)

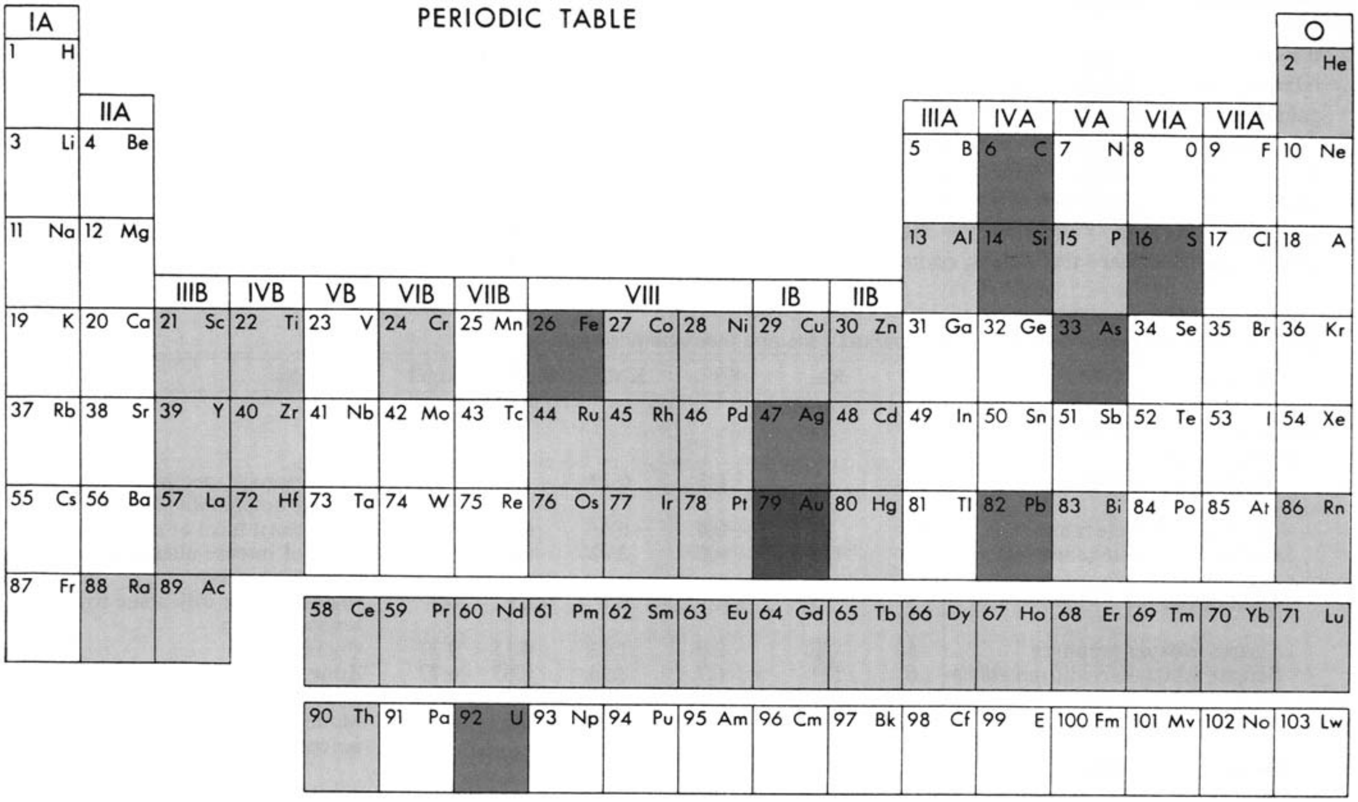
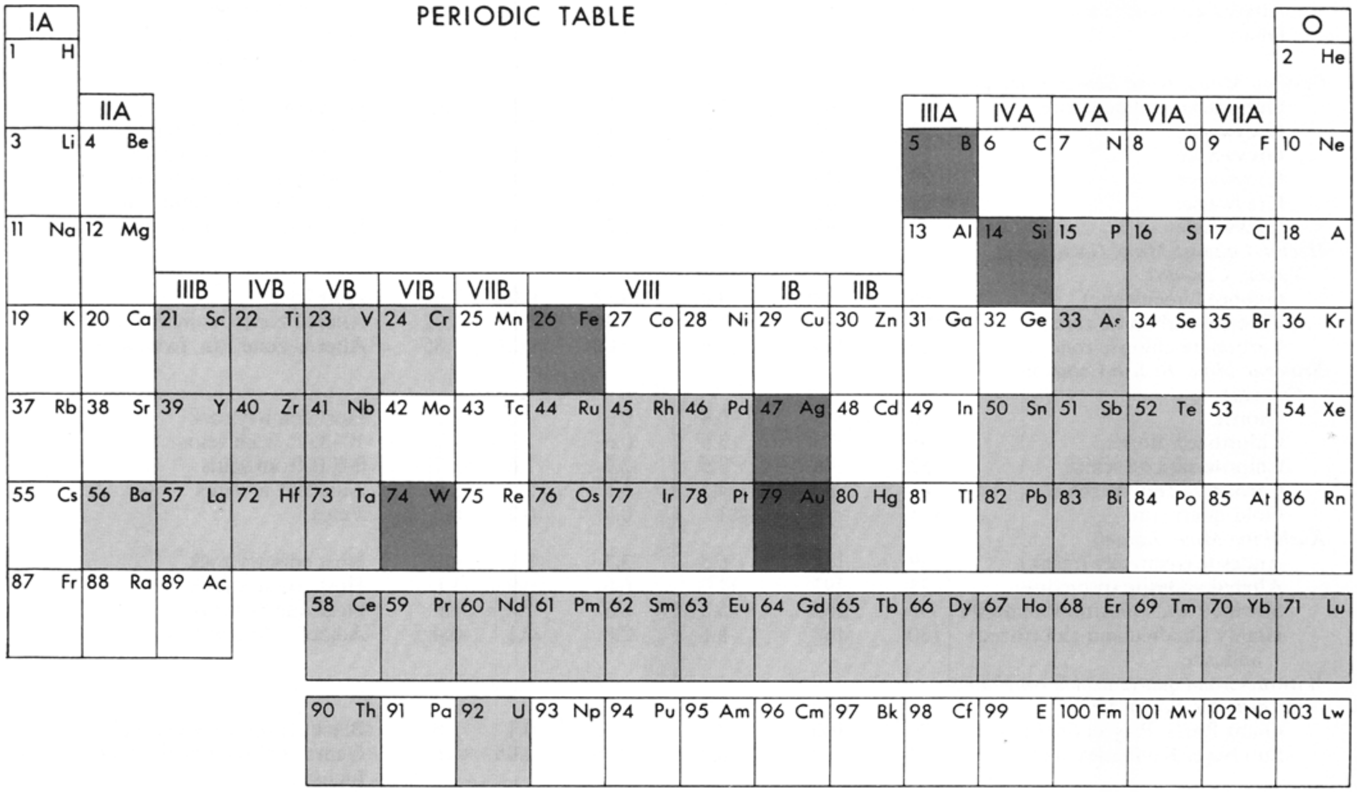


Table 33. Elements associated with gold in eluvial and alluvial placers. Gangue elements are excluded except if present in abnormally high concentrations.



■ *Elements exhibiting a high frequency of enrichment in deposits*

▨ *Elements exhibiting a low or occasional high frequency of enrichment in deposits*

☐ *Elements rarely enriched in deposits*

Contents

the gold deposits that I have investigated, and there are relatively few references to the presence of such minerals in gold deposits described in the literature.

Lithium minerals are occasionally found in skarn deposits, but the gold-bearing sulphide skarn deposits appear to be relatively low in the element according to my analyses. In auriferous skarn in Yukon, at the New Calumet Mine in Quebec and elsewhere the lithium contents ranged from 6 to 17 ppm. Most of the lithium is present in Mg-Fe amphiboles and pyroxenes, tourmaline and micas. There is no correlation between the lithium and gold contents of skarn deposits as far as I can ascertain.

Gold-quartz veins and silicified bodies and their alteration zones generally contain only small amounts of lithium as shown in Table 34. (*See also* the tables accompanying the section on wall-rock alteration processes.) There is a general

Table 34. Alkali element content of some gold deposits and their alteration zones

Description	Li	Rb	Cs	K_2O	Na_2O	MgO	Remarks
		(ppm)			(%)		
*Yellowknife district, N.W.T., Canada**							
Greenstone Belt:							
Amphibolite (greenstone)	16	11	0.3	0.39	1.85	6.53	Country rock; composite sample of epidote amphibolite facies
Chlorite-carbonate schist	49	12	0.4	0.41	0.90	8.43	Main constituent of shear zones
Carbonate-sericite schist	12	106	4.0	2.82	0.29	5.77	Zone of intense alteration adjacent to quartz lenses
Gold-quartz ore	5	5	<1	0.1	<0.1	0.3	Mainly quartz with some pyrite, arsenopyrite, etc.
Quartz-feldspar porphyry	5	58	2.0	1.63	4.15	0.37	Country rock
Sericite schist derived from above	6	171	6.7	3.94	0.63	0.77	Zone of alteration adjacent to quartz veins
Gold-quartz ore	5	5	<1	<0.1	<0.1	0.3	Mainly quartz with some pyrite, arsenopyrite, etc.
*Sedimentary area (Ptarmigan Mine)**							
Greywacke and minor slate	40	63	4	2.2	3.3	3.0	Country rock
Greywacke and minor slate	76	67	6	2.2	3.3	3.0	2–6 ft from vein
Greywacke and minor slate	79	227	47	4.0	2.0	3.1	6–12 in. from vein
Altered greywacke and slate	66	87	10	2.7	2.8	3.0	0–12 in. from vein
Quartz vein	2	2	<1	0.08	0.01	0.03	Mainly quartz with minor pyrite, sphalerite and galena
Caribou Mines, Nova Scotia, Canada							
Greywacke and quartzite	27	65	2.6	1.56	2.8	0.8	Host country rock
Greywacke	20	90	3.6	2.19	2.7	1.1	Host rock, 10 in. from vein
Greywacke	19	88	3.4	2.17	2.6	1.1	Host rock, 7 in. from vein
Greywacke	19	89	3.7	2.30	2.6	1.1	Host rock, 5 in. from vein
Greywacke	22	89	3.7	2.15	2.7	1.1	Host rock, 3 in. from vein
Greywacke	23	90	3.6	2.21	2.7	1.1	Host rock, 1–2 in. from vein
Hector-Calumet Mine, Galena Hill, Yukon, Canada†							
Gabbro (greenstone)	95	32	3.4	0.22	0.04	7.62	Host rock
Chlorite-carbonate zone	94	144	5.6	1.31	0.53	5.32	Altered zone 1–6 in. from lodes
Carbonate-chlorite zone	24	310	11.6	3.00	0.21	1.85	Altered zone 1 in. from lodes
Bralorne Mine, British Columbia, Canada‡							
Diorite	16	5	0.6	0.3	4.0	4.9	Host country rock
Chloritized diorite	38	15	3.5	0.6	2.7	7.2	10–25 ft from veins
Chlorite-sericite schist	52	46	3.5	2.6	1.6	5.7	0–5 ft from veins
Carbonate-sericite schist	47	64	4.2	3.6	2.3	2.4	Adjacent to veins
Gold-quartz ore	<5	<5	<1	0.3	0.2	0.3	Veins
Kushikino Mine, Japan§							
Andesite (relatively fresh)	49	144	6.5	3.7	2.1	4.0	Host country rock
Altered andesite (propylite)	28	293	11.7	6.6	0.9	1.8	Host country rock
Silicified and chloritized andesite	33	252	5.3	6.5	1.8	1.6	Near quartz veins
Highly silicified and chloritized andesite	130	148	8.5	2.8	0.1	0.4	Adjacent to quartz veins
Witwatersrand quartz-pebble conglomerate deposits, South Africa‖							
Giant Reefs, Project 68/61/A	20	100	3.5	2.53	0.1	3.0	Black (carbonaceous) reef
Sub Nigel-Kimberley reef	12	17	<0.1	0.49	0.05	0.6	Quartz-pebble conglomerate, some fuchsite
Welkom basal reefs	2	12	1.5	0.39	0.06	0.06	Quartz-pebble conglomerate

*For description of deposits *see* Boyle (1961*a*).
†For description of deposits *see* Boyle (1965*a*).
‡For description of deposits *see* Joubin (1948).
§For description of deposits *see* Taneda and Mukaiyama (1970).
‖ For description of deposits *see* Liebenberg (1955).

enrichment of lithium in most alteration zones, excepting those in granitic rocks where there is commonly a depletion. No particular pattern is evident with respect to distance from the veins and lodes. Pampura and Trufanova (1968) noted, however, that the inner zones of the argillic alteration halos were enriched in lithium (200 ppm) compared with the zones remote from the mineralization (130 ppm) in the epithermal Balei gold deposit in eastern Transbaikal. Radanova and Karadzhova (1971) also noted concentrations of lithium in the dickite-quartz facies of the propylites in the Tertiary Spahievo Pb-Zn field in Bulgaria. Much of the lithium in the alteration halos and gold ores is present in micas and clay minerals such as sericite and kaolinite, and in Mg-Fe minerals, particularly chlorite and talc; also in tourmaline where this mineral is present in the alteration mineral suite. In some alteration zones lithium tends to follow magnesium and/or iron, a feature that is in agreement with the general geochemistry of the element. There is generally no particular correlation with K_2O such as that shown by rubidium and cesium.

Lithium probably exhibits a behaviour in auriferous polymetallic deposits similar to that noted above for gold-quartz deposits, judging from the results obtained from analyses of the alteration zones associated with the Pb-Zn-Ag lodes at Keno Hill, Yukon (Table 34).

There appear to be no data on the lithium contents of the disseminated gold deposits such as those that occur in Nevada (Cortez, Carlin, Gold Acres) and elsewhere.

There are no data in the literature on the lithium contents of gold-bearing quartz-pebble conglomerates. Analyses done in laboratories of the Geological Survey on samples from some of the reefs of the Witwatersrand system indicate a range in the lithium content from 2 to 20 ppm (Tables 34 and 35). The black (carbonaceous) reef material appears to contain the highest amounts of the element.

Lithium is a common trace element in most hot spring waters. Those in the Taupo volcanic zone of New Zealand, from which gold-silver ore-grade materials are being precipitated, contain 3.2 to 12 ppm Li (Weissberg, 1969).

The behaviour of lithium during the oxidation of gold deposits appears to be erratic (Table 36). In some cases the element is leached from the oxidized zones; in other cases there may be a slight enrichment. I have noted that lithium may be considerably enriched where wad (hydrous manganese oxides) is abundant in gossans.

Table 35. Trace and minor element content of some auriferous quartz-pebble conglomerate deposits

Element	Giant Reefs, Witwatersrand, South Africa	Sub-Nigel-Kimberley Reef, Witwatersrand, South Africa	Welkom Basal Reefs, Witwatersrand, South Africa	Tarkwa, Ghana	Elliot Lake, Ontario
			(ppm)		
Li	20	12	2	6.6	13
Rb	100	17	12	28	100
Cs	3.5	<0.1	1.5	2.0	2
Cu	137	110	86	10	100
Ag	1.6	2.7	8.6	0.2	2.3
Au	4.35	300	98	11.0	0.090
Be	3.5	<2	<2	<2	<2
Sr	136	13	21	105	18
Ba	330	<50	<50	1050	410
Zn	300	330	132	11	10
Cd	2	0.7	0.3	<0.5	1
Hg	0.130	3.28	1.95	0.040	5.0
B	150	20	10	35	25
Ga	5	5	2	5	8
In	<1	<1	<1	<1	<1
Tl	nf	nf	nf	<100	<100
Sc	16	0.7	10	10	10
Y	10	14	25	9	70
La	26	15	21	45	130
Ce	nf	nf	nf	nf	5
Th	2	15	130	27	435
U	0.6	167	1500	0.7	2000
Ge	0.8	1.3	<0.7	<0.5	<0.5
Sn	3.5	5.5	5.0	2.0	3.0
Pb	51	96	450	7	535
Ti	2847	629	839	2877	1468
Zr	47	80	320	220	15
As	13600	108	216	3	28
Sb	2	3	3.5	2	1
Bi	nf	2.2	1.7	nf	43
V	96	18	15	22	2
Nb	12	18	15	4	6
Ta	<3	<3	<3	<3	<3
Se	2	1.5	1	nf	3
Te	<0.2	0.4	0.2	<0.2	0.7
Cr	585	710	705	29	4
Mo	3	2.5	2.5	1	11
W	nf	nf	nf	nf	2
F	195	10	5	25	35
Cl	250	45	15	10	60
Mn	590	108	55	1400	2
Co	37	59	102	16	57
Ni	111	106	158	8	45
Pt	<0.005	<0.005	<0.005	0.020	0.005
Pd	0.025	<0.025	0.062	0.005	0.006
P	7500	100	170	87	300

Note: nf–not found.

Sodium is most commonly associated with hypogene gold deposits, being concentrated in the alteration zones of these deposits, particularly in those in basic to intermediate igneous rocks but also in places in those in granites, shales, slates, skarn, gneisses and similar rocks. Most of the sodium is concentrated in the alteration (metasomatic) feldspars, mainly albite and adularia, with small amounts in sericite (paragonite), chlorite and other alteration minerals. Sodium feldspars (albite or adularia) and micas may also occur in the vein quartz or silicified zones of gold deposits. In places skarn-type gold deposits show an enrichment in sodium, the element being mainly in feldspars and other silicates. Gallagher (1940) and Firsov (1956) have remarked on the frequent occurrence of albite-rich rocks in the vicinity of gold deposits. Reid (1941), Bruce (1941*a*), and Wisser (1944) have commented on this association and have provided a number of exceptions, especially in wall-rock alteration phenomena. The behaviour of sodium in gold deposits is discussed in greater detail in the section on alteration processes.

Potassium is enriched in the alteration zones of many types of hypogene gold deposits, the element occurring mainly in sericite, clay minerals, feldspar (orthoclase, albite and adularia) or alunite. The element is particularly characteristic

Table 36. Alkali element content of some oxidized gold deposits

Description	K_2O	Li	Rb	Cs	Remarks
	(%)		(ppm)		
*Yellowknife Greenstone Belt, N.W.T., Canada**					
Gold-quartz ore, Lynx prospect	1.62	7	53	<1	Contains essentially quartz, pyrite, arsenopyrite and sulphosalts
Gossan, Lynx prospect	0.01	1	<1	<0.1	Mainly limonite with highly leached schist particles
Keno Hill, Yukon, Canada†					
Gold-quartz ore, No. 6 vein	0.16	2	6	0.2	Contains essentially quartz, pyrite and arsenopyrite
Oxidized zone, No. 6 vein	4.5	8	231	18.5	Mainly limonite, quartz and jarosite minerals
Keno Hill, Yukon, Canada†					
Pb-Zn-Ag ore (Hector-Calumet Mine)	0.17	1	2	1.2	Composite sample oxidized ore, 100-foot level, No. 3 vein
Pb-Zn-Ag ore (Hector-Calumet Mine)	0.08	1	7	0.0	Composite sample oxidized ore, 300-foot level, No. 3 vein
Pb-Zn-Ag ore (Hector-Calumet Mine)	0.12	1	14	0.0	Composite sample unoxidized ore, 400-foot level, No. 3 vein
Pb-Zn-Ag ore (Hector-Calumet Mine)	0.09	1	8	0.0	Composite sample unoxidized ore, 525-foot level, No. 3 vein
Pb-Zn-Ag ore (Hector-Calumet Mine)	0.07	1	6	0.0	Composite sample unoxidized ore, 650-foot level, No. 3 vein
Pb-Zn-Ag ore (Hector-Calumet Mine)	0.05	1	2	0.0	Composite sample unoxidized ore, 775-foot level, No. 3 vein

*For description of deposits *see* Boyle (1961*a*).
†For description of deposits *see* Boyle (1965*a*).

of gold-quartz deposits marked by sericitization and alunitization and the development of potassic feldspar, micas and adularia in the vein quartz or silicified zones. Skarn-type gold deposits may also exhibit an enrichment of potassium in places. The disseminated gold deposits (Carlin, Nevada) exhibit a marked enrichment of potassium in the primary ore-bearing parts (1.6%) compared with the host carbonate country rocks (0.7%) (Radtke *et al.*, 1972*a*). Some of the auriferous beds of the quartz-pebble conglomerates have a relatively high potash content (Table 34). Most of the potassium in these deposits is present in micas (sericite). Thermal waters carrying and precipitating gold are invariably enriched in potassium and sodium. Those in New Zealand have potassium and sodium contents ranging from 49 to 224 ppm and 545 to 1785 ppm respectively (Weissberg, 1969). The wall rocks of the fissures carrying the thermal waters are also enriched in potassium (adularia) according to the data provided by Steiner (1970). The oxidized zones of gold deposits frequently show an enrichment in potassium (mainly in jarosite) in gold-rich sections; sodium, on the other hand, is commonly leached out.

The behavior of potassium and sodium in hypogene gold deposits is discussed in greater detail in the section on alteration processes. There, it is shown that the K_2O/Na_2O ratio commonly increases as gold mineralization is approached, a useful feature that can be employed during detailed prospecting for gold-quartz and other types of epigenetic gold deposits (Boyle, 1974*b*).

Rubidium and *cesium* follow potassium closely in gold deposits being concentrated mainly in sericitized and feldspathized alteration zones. The bulk of both elements is concentrated in sericite, potassic feldspars or alunite. I have not observed pollucite or any other cesium or rubidium minerals in gold deposits.

Skarn deposits enriched in potassium may have elevated contents of both rubidium and cesium, but the gold-bearing varieties analyzed in the Geological Survey laboratories were all relatively low in both elements, rarely containing more than 45 ppm Rb and 1 ppm Cs.

Gold-quartz veins and silicified bodies and their alteration zones contain only small amounts of rubidium and cesium as shown in Table 34. In the alteration zones of gold-quartz veins both elements tend to be sympathetically enriched with potassium, increases in the elements being evident as the veins are approached. In the Balei gold-quartz deposits, eastern Transbaikal, Pampura and Trufanova (1968) noted marked enrichments of cesium (average 45 ppm) in the alteration zones. The chief host minerals were found to be kaolinite and hydromica, mainly the latter.

Rubidium and cesium probably exhibit a behaviour in auriferous polymetallic deposits similar to that noted above for the gold-quartz deposits, judging from the results obtained from analyses of the alteration zones associated with the Pb-Zn-Ag lodes at Galena Hill, Yukon (Table 34). Radanova and Karadzhova (1971) noted high concentrations of rubidium and cesium in the propylite facies (13–250 and 0–50 ppm respectively) associated with the Tertiary Pb-Zn deposits in the Spahievo ore district in Bulgaria. Cesium tended to be concentrated in the epidote-chlorite-albite subfacies.

There are no extensive data in the literature on the rubidium and cesium contents of the auriferous quartz-pebble conglomerates. Analyses done in the Geological Survey laboratories on samples from some of the reefs of the Witwatersrand system (Tables 34 and 35) indicate a range for rubidium of 12 to 100 ppm and for cesium <0.1 to 3.5 ppm. The black (carbonaceous) reef material appears to contain the highest amounts of the elements. The range for rubidium given by Feather and Koen (1975) is from <5 to 56 ppm.

There appear to be no data on the rubidium and cesium contents of the disseminated gold deposits such as those that occur in Nevada (Cortez, Carlin, Gold Acres) and elsewhere.

Rubidium and cesium are common trace elements in some hot spring waters, but there are no data on these two elements in gold-bearing hot springs. The data provided by White *et al.* (1963*b*) indicate that up to 0.2 ppm Rb may be present in thermal waters closely associated with certain epithermal mineral deposits.

The behaviour of rubidium and cesium during the oxidation of gold deposits is similar to that of potassium. In some deposits both elements are leached from the oxidized zones; in others there is an enrichment. The latter takes place mainly in gossans and oxidized zones where jarosite minerals are developed, such as in some of the gold-bearing veins at Keno Hill (Table 36). Gold and silver may also be concentrated in these jarosite-rich zones (*see* Chapter IV).

Group IB: Cu, Ag

Copper, varying in amount from traces to a few per cent, is a constant associate of gold in all types of deposits. The element may from a suite of its own minerals and/or may occur as a constituent in a variety of sulphides and sulphosalts and in native gold and its various minerals. The concentration of copper in native gold is highly variable (*see* Chapter II). The most common copper minerals in gold deposits are chalcopyrite, enargite, chalcocite and tetrahedrite-tennantite; in some skarn zones bornite is abundant. The chalcocite zones of certain supergene enriched copper deposits are commonly rich in gold. Native copper occurs in some gold-quartz veins (e.g., Windpass Mine, B.C.; and Ptarmigan Mine, Yellowknife, N.W.T.). In these deposits the mineral is primary in origin. The mineral may also occur in certain oxidized zones of gold deposits but generally only in small amounts.

Some auriferous skarn deposits are greatly enriched in copper; others such as the Nickel Plate Mine at Hedley, British Columbia contain only minor amounts of the element. Both gold and silver tend to follow copper in auriferous skarns, but the relationships are often complex (Table 37).

Most Precambrian gold-quartz deposits and silicified deposits are low in copper as are also most of those in younger epochs. In some of the latter, however, copper may appear in some abundance, especially in Tertiary deposits.

The disseminated gold deposits (Carlin) are enriched in copper (up to 200 ppm; average 35 ppm) in the primary mineralized zones (Radtke *et al.*, 1972*a*). Most of the copper is in chalcopyrite and probably also in sulphosalts.

The quartz-pebble conglomerates usually carry copper, mainly in chalcopyrite; some reefs also contain small amounts of cubanite, bornite, chalcocite, covellite, neodigenite, chalcopyrrhotite (?) and tennantite-tetrahedrite, (Liebenberg, 1955; Saager, 1968; Feather and Koen, 1975). Analyses of a number of the reefs done in the Geological Survey laboratories show copper contents ranging from 10 to 137 ppm (Table 35). On the basis of only a few samples it appears that the carbonaceous reefs are the richest in the metal.

Hot springs carrying and precipitating gold invariably carry some copper. The amounts are usually small (0.002–0.2 ppm) in the water.

Gold is positively correlated with copper in some hypogene deposits; in others there is no particular relationship. The old Chilean proverb "If thou findest copper, thou has gold" is, therefore, not universally true. The zoning relationships of copper with respect to gold are discussed in the last part of this chapter and shown in Figures 94 and 95. Near vein and other types of epigenetic gold deposits, copper commonly increases in content as the veins are approached. (*See* the section on wall-rock alteration processes and the accompanying tables.)

In oxidized copper deposits, and in some gold deposits, the secondary chalcocite and other supergene sulphide zones are greatly enriched in gold (and silver). In the gossans and oxide zones of many polymetallic, massive sulphide and gold deposits copper and gold tend to part company – the gold largely remaining behind and the copper being removed to lower levels or dispersed in the groundwaters. In a few oxidized gold deposits azurite, malachite, chrysocolla and other secondary copper minerals may accompany rich auriferous parts of gossans. (*See also* Chapter IV.)

Silver, varying from traces to minor amounts, is a constant associate of gold in all types of deposits. The element may form its own suite of minerals and/or may occur as a trace constituent of various sulphides and sulphosalts and in minor or major amounts in native gold and its minerals. The most common silver-bearing mineral in gold deposits is probably tetrahedrite-tennantite. Argentite (acanthite) is common in some vein deposits younger than Precambrian, as are also proustite and pyrargyrite. Other silver sulphosalts tend to be rare. Silver tellurides are common in deposits in volcanic rocks in places. The selenide, naumannite and other silver selenides occur sparingly in certain Tertiary deposits. Silver-bearing minerals in the quartz-pebble conglomerates of the Rand, exclusive of gold, include tennantite, stromeyerite, proustite and rarely native silver and dyscrasite (Saager, 1968; Feather and Koen, 1975). Native silver is relatively rare in the hypogene parts of most gold deposits, although it has been recorded in a few deposits of all ages. In most places it appears to represent a stage in the mineralization that is quite

Table 37: Gold, silver, copper, K_2O and Na_2O content of skarn, Whitehorse Copper Belt, Yukon

Rock type	Au	Ag	Au/Ag	Cu	Cu/Ag	K_2O	Na_2O
	(ppm)			(ppm)		(%)	
Diorite-granodiorite	<0.005	0.2	<0.02	15	75	1.2	2.8
Skarn adjacent to above	<0.005	0.45	<0.01	22	48.8	1.2	4.4
Normal skarn	<0.005	0.2	<0.02	12	60	0.1	0.2
Skarn adjacent to magnetite-bornite deposit	0.05	1.5	0.03	3900	2600	~0.1	~0.2
Magnetite-bornite deposit	5.0	60	0.08	6.4%	1066.6	~0.1	~0.1
Crystalline limestone adjacent to above	0.05	0.1	0.5	135	1350	<0.1	<0.1
Crystalline limestone	<0.005	~0.05	<0.1	5	~100	<0.1	<0.1

Note: Traverses across granodiorite, skarn, copper deposit and limestone at Arctic Chief Mine.
For geology *see* Kindle (1964) and Figure 10.

separate from that of gold. Native silver is common in some of the oxidized zones of auriferous deposits.

The Au/Ag ratio of both native gold and of gold deposits as a whole is variable depending on the many factors discussed in a later section. The silver and gold contents of some hypogene deposits exhibit a definite positive correlation; in other deposits there is no particular relationship. The zoning relationships of silver with respect to gold are discussed in the last part of this chapter and shown in Figures 94 and 95. With respect to the loci of gold (and silver) mineralization in veins and similar deposits, silver generally exhibits a consistent increase in content as the deposits are approached. (*See* the section on wall-rock alteration processes and the accompanying tables.)

Silver and gold are frequently concentrated together in supergene sulphide (mainly chalcocite) zones of oxidized polymetallic, massive sulphide, porphyry copper and gold deposits. In the gossans and oxide zones of these deposits the chemistry of gold and silver is complex and is discussed in Chapter IV.

Group IIA: Be, Mg, Ca, Sr, Ba, Ra

Beryllium frequently exhibits a slight enrichment in the alteration zones of certain types of gold deposits, particularly the vein types where abundant sericite and tourmaline are developed. In the sericite phases of the hypogene alteration in the greenstone belt at Yellowknife the beryllium content (~ 2ppm) appears to vary directly with the amount of sericite present. In other deposits the element appears to be present mainly in tourmaline (up to 15 ppm), and the content of the element varies with the abundance of this mineral. The author has observed no beryllium minerals in hypogene gold vein deposits, but Ol'shevskii (1973) has noted the occurrence of beryl (aquamarine) in some gold-quartz veins of the Karalveem deposit, and beryllium minerals, including beryl, phenakite and bavenite have been reported in some of the auriferous veins of the Hohe Tauren in Austria (Ertl *et al.*, 1975). In skarn deposits containing enrichments of gold, beryllium may exhibit a slight concentration, the element being present mainly in various lime silicates and in minerals such as vesuvianite, helvite, humite, etc. Radtke *et al.* (1972*a*) record <1 to 3 ppm Be in the primary ores of the Carlin, Nevada disseminated ores and <1 to 1 ppm in the host carbonate rocks indicating a slight enrichment of the element during mineralization. In the 'oxidized ores' they found <1 to 3 ppm indicating no particular enrichment during oxidation.

The beryllium content of the Witwatersrand reefs range from <2 to 3.5 ppm (Table 35). The location of the beryllium is probably in the micas and tourmaline. Other quartz-pebble conglomerate deposits show a similar range in the content of beryllium.

The writer has not traced the fate of beryllium during the oxidation of gold deposits in detail. Some analyses of gossans suggest that the element is concentrated in clay minerals and aluminous limonite; the beryllium in tourmaline goes with the mineral into the resistates, which may collect in the soils and nearby streams.

Beryl and other berylliferous minerals may accompany native gold in certain eluvial and alluvial placers, but in most deposits of this nature these minerals are relatively rare.

Magnesium is a frequent associate of gold particularly in skarns and in vein deposits in intermediate and basic rocks. In skarn the element forms a large number of magnesium silicates and spinels; in vein deposits the element is present mainly in chlorite, talc, serpentine, biotite and similar minerals and in magnesian calcite, dolomite and ankerite. All of these minerals may also occur in the vein quartz and in silicified zones. Magnesite appears to be rare in gold deposits, although it has been reported in some according to the old literature. Much of the magnesium in gold deposits appears to have been derived from the host rocks. (*See further* under the section on wall-rock alteration processes.)

During oxidation processes in gold deposits large amounts (commonly more than 75%) of magnesium are leached. Some magnesium is, however, retained in the gossans and oxidized zones mainly in the forms of supergene carbonates and secondary chloritic minerals.

Spinels may appear in the heavy concentrates of some gold placers. A host of other magnesium minerals may also be present including garnets, amphiboles, pyroxenes, etc.

Calcium is universally present in all types of hypogene gold deposits. In skarn deposits the element forms a number of calc-silicates and may be present in minerals such as fluorite, apatite, sphene and scheelite. In vein deposits calcium is a major constituent of the carbonates of the alteration zones and is frequently present in this form in the quartz veins and silicified zones. The principal calcium carbonates in gold deposits in their order of abundance are ankerite, dolomite and calcite. Anhydrite and gypsum are found in a great variety of gold deposits, mainly vein types, often in some abundance. These two minerals occur both in the alteration zones and in the vein quartz and silicified zones. Large amounts of anhydrite and gypsum are a feature of some of the deposits in the Timmins (Porcupine) area, Ontario, and the two minerals have been noted by the writer in a number of gold deposits in various greenstone belts in Canada.

Much of the calcium in gold deposits appears to have been derived from the host rocks. (*See further* under the section on alteration processes.) In some deposits, however, there is evidence to suggest that the calcium has been introduced from distant sources.

During the oxidation of gold deposits much calcium is lost, commonly more than 50 per cent. Some calcium is, however, retained in the gossans and oxidized zones mainly in the form of supergene carbonates, gypsum and anhydrite.

In placer deposits the most persistent calcium minerals associated with native gold appear to be sphene and garnet. A host of other calcium minerals may also be present in varying amounts, including various silicates, apatite, scheelite, etc.

Strontium tends to follow calcium in most hypogene gold deposits, being concentrated in small amounts mainly in the various hypogene carbonates and alteration zones. At Yellowknife, and in other gold deposits in greenstone belts in Canada, the strontium content of the carbonates rarely exceeds 500 ppm. In the carbonate alteration zones in basic and intermediate igneous rocks the amounts of strontium usually range from 20 to 50 ppm Sr. Strontianite appears to be rare in gold deposits as is celestite, although small amounts of the mineral have been recorded in the Kirkland Lake deposits, at Cripple Creek in Colorado and elsewhere. Both strontianite and celestite may occur in small amounts in gold-bearing polymetallic deposits. Most of the strontium in hypogene gold deposits appears to be locally derived, mainly from the nearby host rocks. In the quartz-pebble conglomerate deposits the contents of strontium range from 13 to 136 ppm (Table 35). Much of this strontium is probably in feldspar, the remainder in minerals such as mica. In the disseminated ores at Carlin, Nevada, Radtke *et al.* (1972*a*) recorded the following strontium contents in ppm in the host carbonate rocks, 'primary ores' and 'oxidized ores', respectively: 150 to 2000 (av. 625); 20 to 1500 (av. 150); and 20 to 2000 (av. 140). The averages indicate a depletion of strontium during primary mineralization and practically no change during oxidation processes.

During the oxidation of most auriferous deposits, strontium generally follows calcium and is commonly extensively leached. Some remains behind in the gossans and oxidized zones, mainly in the supergene carbonates.

Barium tends to follow potassium and calcium in hypogene gold deposits being concentrated in small amounts in the various potash feldspars, sericite and carbonates in the wall-rock alteration zones of vein-type deposits. In skarn deposits the element is evidently concentrated mainly in the calc-silicates but again only in very small amounts. At Yellowknife, the carbonates in the wall-rock alteration zones and in the veins rarely contain more than 50 ppm Ba and the sericite-carbonate alteration zones average about 150 ppm. Similar conditions prevail in deposits in greenstone in other volcanic belts of the Canadian Shield. Where the veins occur in intermediate igneous rocks (syenite, granodiorite), however, as at Kirkland Lake and Red Lake, Ontario (Red Lake Gold Shore Mine) barium contents up to 1000 ppm may be recorded in the alteration zones. Barium is apparently also more abundant in certain wall-rock alteration zones in other parts of the world as can be readily seen by perusing the various analyses given by Lindgren (1933) and others. These analyses quote contents up to 1200 ppm Ba, principally in altered intermediate rocks such as monzonite and diorite. The association and correlation of gold with barium in auriferous deposits and their alteration zones is also noted by a number of investigators in U.S.S.R. (Roslyakova and Roslyakov, 1975). In most gold deposits studied by the writer strontium generally exceeds barium in the carbonates by a factor of 2 or more. In the wall-rock alteration zones strontium either equals or exceeds barium where carbonatization is marked. This appears to be a generality judging from analyses quoted in the literature, although there may be some exceptions. (*See also* the section on alteration processes.)

Barite occurs as a minor gangue mineral in some gold deposits, mainly the low and medium temperature types (the epithermal and mesothermal deposits of Lindgren). Witherite and other barium minerals have not been seen by the writer in gold deposits, and there appears to be no reference in the literature to the occurrence of these minerals in auriferous deposits.

The disseminated gold ores of Carlin, Nevada are greatly enriched in barium, present mainly in barite. Radtke *et al.* (1972*a*) report the following barium contents in ppm in the host carbonate rocks, 'primary ores' and 'oxidized ores', respectively: 27 to 1000 (av. 150); 150 to 70 000 (av. 2200); and 200 to 100 000 (av. 2300). The averages indicate only a slight enrichment during oxidation processes.

In the quartz-pebble conglomerate deposits barium occurs in amounts ranging from <50 to 1050 ppm (Table 35). Most of this barium appears to be present in feldspars, the remainder in micas.

Barite, having a relatively high specific gravity and general resistance to weathering and erosion, may accompany the heavy resistate suite of minerals in certain eluvial and alluvial gold placers of recent and ancient derivation. Under conditions of intense weathering and leaching much barium may go into solution and be removed from the gossans and oxidized zones of auriferous deposits. Considerable amounts usually remain behind, however, adsorbed or combined with manganese oxides (wad) and manganiferous limonite. Some is also retained in various supergene sulphates and basic sulphates.

Radium accompanies gold only in those deposits containing uranium and/or thorium. The classic example of such deposits is the Witwatersrand quartz-pebble conglomerates of South Africa. Similar gold deposits in other parts of the world, such as those at Jacobina in Brazil, also carry some radium. Uraninite, pitchblende and thorium minerals, and hence radium, are relatively rare in vein and stockwork gold deposits and in gold-bearing silicified zones and skarn. Exceptions to this generally are met in uranian and thorian metallogenic provinces. Thus, the Richardson Gold Mine in skarn at Eldorado, Ontario carries uraninite, brannerite and thucholite and contains radium; similarly some gold deposits (e.g., the Box and Nicholson mines) in the Beaverlodge uraniferous province of Saskatchewan contain pitchblende and hence carry radium. Other hypogene gold deposits, frequently of Tertiary age and localized in porphyries and granitic rocks, in various parts of the world, carry radium if present in uranium and thorium provinces. (*See also* the section on uranium and thorium.)

During the oxidation of uraniferous and thorium-bearing gold deposits radium behaves much like barium. It tends to be strongly absorbed by wad and manganiferous limonite and may be concentrated in secondary sulphates and basic sulphates. The gossans and oxidized zones may, therefore, be highly radioactive. Under conditions of intense weathering and leaching much radium is removed from the gossans and oxidized zones in a soluble form.

Eluvial and alluvial placers, both recent and fossil, are commonly marked by the occurrence of various uranium- and thorium-bearing resistate minerals such as zircon, monazite, thorite, etc. These normally contain traces of radium.

Group IIB: Zn, Cd, Hg

Zinc is a nearly universal associate of gold in all types of hypogene gold deposits, occurring mainly in sphalerite and a great variety of zinc-bearing sulphosalts; occasionally in franklinite as in some veins in Burma. In some deposits zinc may be present in percentage amounts, in others only as traces or minor quantities. In polymetallic and some skarn deposits for instance the element is invariably abundant; in gold-quartz veins and silicified deposits zinc is a minor element; and in the quartz-pebble conglomerate type of gold deposits is it present generally only in minor amounts (10–330 ppm) according to our analyses (Table 35), mainly in sphalerite (Liebenberg, 1955; Saager, 1968; Feather and Koen, 1975). In some hypogene gold deposits there is frequently a positive correlation between the quantities of zinc and gold in the ores, and the zinc minerals (sphalerite and sulphosalts) are direct indicators; in other deposits no such relationships are evident. The zoning relationships of zinc with respect to gold are discussed in the last part of this chapter and shown in Figures 94 and 95.

In the oxidized zones of gold deposits, gold and zinc tend to part company, the gold remaining behind in the gossans and oxidized rubble of the deposits and the zinc migrating away in the oxidizing meteoric waters. In some deposits, however, the situation is more complex: Zinc may be concentrated together with gold in the supergene sulphide zones, and in the oxidized zones zinc silicates (calamine) and carbonates (smithsonite), and minerals like adamite ($Zn_2(OH)AsO_4$) may be developed where gold is enriched. This seems to take place mainly where the wall rocks are carbonates or where an abundance of dissolved arsenates or colloidal silica was present in the supergene solutions.

The writer has no extensive data on the occurrence of zinc in recent and fossil eluvial and alluvial gold placers. I have, however, noted higher than average amounts of zinc in the heavy mineral fractions of some of these deposits. Most of the zinc is present mainly in magnetite, in residual grains of sphalerite and in particles of wad and limonite. In the clay fractions of eluvial gold deposits I have noted slight concentrations of zinc in places; presumably this zinc is present in an adsorbed form or perhaps in some kind of a zinc clay mineral like sauconite.

Cadmium follows zinc closely in hypogene gold deposits and is generally quantatively contained in sphalerite and zinc-bearing sulphosalts, particularly tetrahedrite and tennantite. The galena and chalcopyrite of some gold deposits may also contain up to 200 ppm cadmium. In the writer's experience gold ores rarely contain more than 500 ppm Cd; more generally these ores contain only from 5 to 60 ppm Cd. Those of the quartz-pebble conglomerate deposits contain from <0.5 to 2 ppm Cd (Table 35). The author has no data on the correlation tendencies of Cd and Au in gold ores. The geochemistry of cadmium in various types of ores, including those bearing gold, is discussed at length in Vlasov (1966).

In the oxidized zones of gold deposits gold and cadmium tend to part company, the gold remaining behind in the gossans and oxidized parts of the deposits and the cadmium migrating away in the oxidizing meteoric waters. In some deposits, however, the situation is more complex. I have noted the presence of relatively high amounts of cadmium in the lower parts of some oxidized zones. Most of this cadmium is precipitated as hawleyite (βCdS) or greenockite (αCdS) on pyrite. Where supergene zinc and lead minerals such as smithsonite, anglesite, beudantite, bindheimite and pyromorphite are present cadmium may be significantly enriched. Limonite, wad and secondary clay minerals may also concentrate small amounts of cadmium. Cadmium may also exhibit a slight concentration in the supergene sulphide zones of certain auriferous deposits. Further details on the fate of cadmium during oxidation processes in mineral deposits can be found in the papers by Boyle (1965*a,b*) and Goleva and Chitaeva (1973).

The writer has no extensive data on the content of cadmium in recent and fossil eluvial and alluvial gold placers. The data available suggest that the element is normally very low in these deposits since only traces have been found in the heavy mineral concentrates. In these, most of the cadmium appears to be in oxidized residuals of galena, sphalerite and sulphosalts and in particles of wad and limonite.

Mercury is a common associate of gold in practically all types of hypogene gold deposits, but the element is invariably present only in small amounts, often much less than 1 ppm in the gold ores as a whole. In some deposits, however, mercury may be more abundant. Many of these are near-surface (epithermal) veins that occur in known mercuriferous belts in various parts of the world. Most of the gold deposits enriched in mercury are young, often of Tertiary age. However, deposits containing marked amounts of mercury are known in Precambrian rocks in Rhodesia (Robertson, 1972), in eastern Ontario and elsewhere. Cinnabar, metacinnabar, livingstonite and mercurian tetrahedrite and tennantite may appear in gold deposits, but they are generally not abundant. Examples of deposits where cinnabar and minor amounts of the other mercurian minerals accompany gold include Mercur, Utah (Spurr, 1923); White Caps Mine at Manhattan, Nevada (Spurr, 1923); a number of Paleozoic deposits in Uzbekistan and the southern Tien-Shan, U.S.S.R. (Finkelshtein, 1970; Rakhmatullaev, 1970); in certain deposits in Azerbaijan S.S.R. (Nasibov *et al.*, 1972); in some deposits in Yakutia (Obolenskii and Obolenskaya, 1972); in a number of mines along the 'Antimony Line' in the Murchison Range in the northeastern Transvaal, South Africa (Sahli, 1961); and in the Carlin deposit in Nevada (Radtke *et al.*, 1972*a,b*). In all of these deposits the mercury minerals are invariably late and commonly associated with stibnite and arsenic minerals such as orpiment and realgar. Coloradoite, HgTe, appears to have a relatively widespread geographical and age distribution in gold-quartz veins, occurring in the Precambrian deposits of Kalgoorlie (kalgoorlite) in Western Australia and at Kirkland Lake, Ontario and in the Tertiary veins of Boulder County, Colorado and elsewhere. Tiemannite, HgSe, may occur in deposits enriched in selenium; Robinson (1955) records its presence in the Nicholson Mine in the Goldfields area, Saskatchewan. Gold accompanies cinnabar and metacinnabar in the active solfatara fields of the Mendeleev volcano in the Kurile Islands (Ozerova *et al.*, 1969).

The general range in the mercury content of some gold deposits is shown in Table 38. Several features are evident from the data. The first is that the age of the deposits seems to have relatively little control on the presence of mercury since certain Precambrian deposits have as much as or more mercury than the younger Tertiary deposits. The deciding factor seems to be the presence of sphalerite and/or late sulphosalt minerals such as tetrahedrite-tennantite. This is especially notable at Yellowknife (greenstone belt), Campbell

Table 38. Mercury content of some gold ores

Description	Hg content (range or average) (ppm)	Remarks
Yellowknife, N.W.T., Canada		
Deposits in greenstone belt	0.025–11.5	Precambrian (Archean) gold-quartz deposits with pyrite, arsenopyrite, stibnite, various sulphosalts, sphalerite, galena, etc.
Deposits in sedimentary area	0.013–0.050	Precambrian (Archean) gold-quartz veins containing pyrite, arsenopyrite, galena and sphalerite
Contwoyto Lake, N.W.T., Canada	0.020	Precambrian (Archean) disseminated native gold deposits in arsenopyritic and pyritic sediments
Red Lake, Ont., Canada		
Red Lake Gold Shore Mine	0.109–0.183	Precambrian (Archean) quartz veins in granodiorite and granite
Campbell Red Lake Mine	0.234–15.4	Precambrian (Archean) quartz bodies in greenstones. Some of the ores are rich in stibnite and sulphosalts
Cochenour Willans Mine	0.04	Precambrian (Archean) silicified bodies in greenstones and iron-formation
Kirkland Lake–Larder Lake district, Ont., Canada		
Macassa Mine	0.020–0.040	Precambrian (Archean) gold-quartz veins in syenite and metasediments
Upper Canada Mine	2.4–25.0	Precambrian (Archean) tabular veins, lenses and silicified zones in volcanics and tuffs
Kerr Addison Mine	0.066–0.180	Precambrian (Archean) gold-quartz veins, stockworks and silicified zones in chlorite schists (greenstones)
Ramore area, Ont., Canada		
Ross-Holtyre Mine	25.3	Precambrian (Archean) gold-quartz veins with abundant sulphides in greenstones
Cordova, Ont., Canada		
Cordova Mine	0.017–0.040	Precambrian (Grenvillian) gold-quartz veins in gabbro
Goldfields, Sask., Canada		
Box Mine	0.036–0.048	Precambrian (Archean) gold-quartz stockwork in granite sill
Sudbury, Ont., Canada		
Vermilion Mine	0.033–0.053	Precambrian (Proterozoic) massive sulphide ore greatly enriched in Au and platinoids
Keno Hill, Y.T., Canada		
No. 6 vein, Keno Hill	0.40	Mesozoic(?) gold-quartz veins with abundant arsenopyrite and sulphosalts in quartzites and phyllites
Dublin Gulch, Potato Hills	0.026–0.368	
Bridge River district, B.C., Canada		
Bralorne Mine	0.072–1.9	Mesozoic gold-quartz veins in diorite
Nova Scotia, Canada		
Various mines in Meguma Formation	0.040–0.319	Paleozoic gold-quartz veins and saddles in greywacke and slate
Japan		
Kushikino Mine	0.150	Tertiary gold-quartz veins and lenses in silicified andesite
Hauraki Goldfield, New Zealand		
Martha Mine	2.5	Tertiary gold and sulphide deposits in andesites and associated rocks
Maratoto Mine	0.122	
Tui Mine	0.060	
Waihi Mine	11.69	
Puhipuhi, New Zealand		
Puhipuhi hot springs	360–760	Slightly auriferous siliceous sinter
Witwatersrand, South Africa	0.130–3.28	Precambrian (Archean?) quartz-pebble conglomerates
Dublin Gulch, Y.T., Canada	765–5350	Gold nuggets in Tertiary(?) placer

Red Lake and the Ross-Holtyre Mine. At Yellowknife, orebodies with little sphalerite and few sulphosalts contain low contents of mercury (0.025–0.10 ppm) whereas those rich in sulphosalts are generally enriched in mercury (>5 ppm). The Ross-Holtyre Mine is unusual in that it has one of the highest mercury contents of any gold deposit examined in the Canadian Shield. This mine is also unusual in other respects – it has an Au/Ag ratio much less than 1 for some of its orebodies, a feature that is anomalous compared with most gold deposits in the Canadian Shield of Ontario. Two periods of mineralization are present in places, the first a gold-quartz one and the second quartz-dolomite veins with sphalerite, tennantite, gold, niccolite and native silver (Jones, 1948*b*). The last two minerals are reminiscent of Cobalt, Ontario where the mineralization, especially the native silver, is enriched in mercury. Another feature of the data on mercury is that deposits in volcanics appear on the whole to contain more of the element than those in sedimentary terranes. This is exemplified again at Yellowknife when a comparison between deposits in the greenstones and those in the sedimentary area are considered. In this case sphalerite is not a factor since both types of deposits contain about equal amounts of the mineral. The deposits in the sedimentary area, however, contain no sulphosalts, and this may be the controlling factor. Yet another feature is the general enrichment of mercury in the ores of the Witwatersrand. This is paralleled by similar enrichments of mercury in the Elliot Lake deposits (Table 35). The final feature of note is the great enrichment of mercury in some gold nuggets compared with the amount of the metal in the primary deposits as in the Dublin Gulch area of Yukon. This feature is discussed in more detail in the section on placers in this chapter.

To summarize, one can say that the content of mercury in gold deposits is relatively independent of age, the controlling factors being the presence of sphalerite and/or sulphosalts and cinnabar. In general, however, Tertiary deposits tend to be enriched in mercury compared with older deposits. Deposits in volcanics tend to contain more mercury than these in sedimentary terranes. From the literature it is evident that primary gold deposits, and the gold in placers, in mercuriferous belts contain much more mercury than those outside these belts, although there are exceptions to this generalization.

Sears (1971) examined the distribution of mercury in selected base metal and gold deposits in Quebec, Canada. He found that mercury was more abundant in zinc sulphide ores than in iron, copper or lead sulphides and that, generally, there was an increase in mercury with increasing zinc content of the ore.

Two base metals mines from the Grenville Province of the Precambrian Shield (New Calumet and Montauban) were found to have the highest tenors of mercury of all ores sampled, followed by the base metal ores of the Superior Province of the Precambrian Shield, the Appalachian region and the St. Lawrence Lowlands.

Samples from three gold deposits (Camflo, Sigma and Lamaque mines) in the Superior Province showed that contrary to expectations the gold ores were extremely low in mercury (0.001–0.125 ppm). Sears (1971) commenting on this feature noted that this was the reverse to that found for gold deposits in the United States and Sweden (James, 1962, 1964; Akright *et al.*, 1969).

Tsonev (1972) examined the relationships of gold and mercury in the Radka deposit, Bulgaria and found that the late stage native silver contained the highest amounts of the element.

Radtke *et al.* (1972*a,b*) found an enrichment of mercury in the disseminated Tertiary gold ores at Carlin, Nevada. The fresh carbonate rocks contain from 0.02 to 0.24 ppm Hg (av. 0.08); the mineralized carbonate rocks or 'primary ores' from 0.4 to 453 ppm Hg (av. 25 ppm); and the oxidized mineralized rocks or 'oxidized ores' from 0.2 to 130 ppm Hg (av. 20 ppm). These contents compare with average zinc values as follows: fresh carbonate rocks (14 ppm), 'primary ores' (185 ppm) and 'oxidized ores' (110 ppm).

In a recent paper Jonasson and Sangster (1975) report the mercury contents of a large number of samples of sphalerite from Canadian sulphide deposits, some of which carry gold. They noted that the significant factors which influence the magnitude of the mercury levels include age and type of deposit, bulk composition of the ore (proportion of zinc and perhaps lead) and proximity to postore activation or reactivation of regional fault structures. With respect to the age of the host rocks, mercury in sphalerite in sulphide deposits in volcanic terranes varied in its mean relative abundance as follows: Proterozoic (99 ppm)>Phanerozoic (50 ppm)>Archean (33 ppm). In carbonate-hosted deposits, the order of abundance was similar: Proterozoic (~10 ppm)>Phanerozoic (3.7 ppm). The mercury contents of sphalerite in Zn- and Pb-rich deposits in volcanic terranes were generally higher than those in the Cu-rich ones. Sphalerites in deposits which contain sulphosalt minerals (generally Pb-Zn, Ag ores), e.g., tetrahedrite, were found to be high in mercury. Mercury contents, up to 450 ppm were found in sphalerite in the sulphide deposits in volcanic terranes in the Flin-Flon–Snow Lake–Lynn Lake belts – the highest found for deposits of this kind in the Canadian Shield.

In most gold deposits the bulk of the mercury is present principally as a trace constituent in the various sulphides, arsenides and sulphosalts, particularly sphalerite and tetrahedrite-tennantite. Analyses performed at the Geological Survey show great differences in the amount of mercury present in these minerals in gold deposits, the range in the sphalerite being 0.1 to 200 ppm and in the tetrahedrite-tennantite 10 to 1000 ppm. We have noticed that mercurian tetrahedrite (with $Hg > 1\%$) generally tends to be very low in silver and gold content, and the reverse is also true that argentian tetrahedrite-tennantite with as much as 5 per cent Ag and 45 ppm Au tends to be remarkably low in mercury, containing amounts usually less than 5000 ppm Hg. The reason for this is not clear. It should be noted, however, that a new variety of argentian mercurian tetrahedrite has been described by Atanasov (1975) from the Chiprovtsi lead-silver deposit, western Stara-Planina mountains, Bulgaria. This tetrahedrite contains more than 16 weight per cent Ag and more than 18 weight per cent Hg; the gold content is not given. The mineral has an extremely large unit-cell edge, $a = 10.64 \pm 0.01$ Å. The argentian mercurian tetrahedrite is associated with a late stage pyrite-cinnabar mineralization.

Native gold, in most of the gold deposits examined by the author, contains mercury, but the amounts are highly variable ranging from mere traces in some deposits to several hundreds and even thousands of parts per million in others. The gold, both hypogene and placer, in the mercuriferous belts of the earth's crust seems to contain the highest contents of mercury. Where native silver occurs in auriferous deposits it may be greatly enriched in mercury.

Relatively little is known about the fate of mercury during the oxidation of gold deposits. Only generalizations can be made. The author has found that during the weathering and oxidation of deposits containing mercury, the element enters the exogene (surficial) cycle as compounds that are both of a physical and chemical nature (Jonasson and Boyle, 1972). Both cinnabar and native mercury are relatively stable to oxidation during weathering processes and may pass into the soil and ultimately into stream and lake sediments as finely divided particles of these two minerals. In its chemical forms mercury passes into the surficial cycle as the metal, Hg^0, and its two ions, Hg_2^{2+} and Hg^{2+}. Mercury metal is relatively soluble (6×10^{-5} g/L; 60 ppb) under practically all Eh and pH conditions found in nature. The ions exhibit variable solubilities depending upon the anionic species available and the Eh-pH regime. The author's experience suggests that mercury in most surficial waters can migrate as sulphate, nitrate, various chloride complexes, carbonate complexes, hydroxide complexes, ammonia complexes, methylated forms, e.g., $Hg(CH_3)_2$, and as a variety of chelated and other organometallic complexes resulting from the decay of plant and animal matter and the maturation of humus. Precipitation of the small amounts of mercury in downward percolating waters in ore deposits takes place mainly by adsorption on inorganic materials such as limonite, wad, etc. and by adsorption and/or chelation or other forms of organic binding by humic constitutents if present in the oxidized zones. Production of H_2S by inorganic processes or by bacteria in the vein systems precipitates the element as the sulphide in the secondary sulphide zones of some deposits. Under extremely arid conditions or where sodium chloride or other chlorides are available from sea winds, salt pans, saline waters, etc. the minerals montroydite, HgO, calomel, Hg_2Cl_2, and a number of oxychlorides such as terlinguaite, Hg_2OCl, and eglestonite, Hg_4OCl_2, may be developed in the oxidized zones. Mercurian tetrahedrite in some deposits oxidizes to give pulverulent cinnabar where the oxidation potential is moderately low as in the lower parts of the oxidized zones. Native gold (and silver) in oxidized zones tends to collect mercury and may become enriched in the element in some deposits.

Under most conditions mercury is lost from the oxidized zones of gold deposits especially where the oxidation has been intense and prolonged. Where the conditions are less severe mercury may exhibit an enrichment. At Yellowknife the gold ores in the greenstone belt average about 0.375 ppm Hg; gossans where developed contain up to 1.2 ppm Hg, indicating a general enrichment. At Clyde Forks, Lanark County, Ontario the gold-bearing tetrahedrite-cinnabar occurrence averages about 5000 ppm Hg and the gossanous material, where developed, averages about 500 ppm. At Carlin, Radtke *et al.* (1972*a*) report values of 0.4 to 453 (av. 25) and 0.2 to 130 (av. 20) ppm Hg respectively for the mineralized carbonate rocks (primary ores) and oxidized mineralized rocks (oxidized ores) respectively, indicating some loss of mercury during oxidation processes. In the oxidized ores the mercury is present mainly as remnant cinnabar and secondary schuetteite, $Hg_3(SO_4)O_2$, montroydite, HgO, and minor amounts of the native metal.

Mercury is present in relatively large amounts in some gold placers; the element occurring usually as cinnabar but also occasionally in the form of secondary minerals such as native mercury and calomel. Mercury is also a trace or minor constituent of most samples of placer gold, especially in mercuriferous terranes.

Group IIIA: B, Al, Ga, In, Tl

Boron is commonly associated with gold in practically all types of its deposits. The most frequent boron mineral in auriferous deposits is tourmaline, much less frequent are danburite, datolite, axinite, dumortierite, kotoite and ludwigite. Tourmaline is particularly characteristic of certain gold-quartz veins and silicified zones in greywacke and pelitic sedimentary rocks and their metamorphic and granitized equivalents including most granitic rocks; it is usually less abundant in veins in diorite and greenstone. Axinite and dumortierite tend to occur most frequently in skarn-type deposits, although these two minerals and danburite and datolite, sometimes occur in near-surface (epithermal) and deeper seated gold-quartz deposits. Kotoite and ludwigite are practically restricted to skarn-type deposits, particularly those enriched in copper. Boron is enriched in the disseminated gold deposits (Carlin type) in amounts ranging from <7 to 200 ppm (av. 79 ppm) as compared with the carbonate host rocks from <7 to 70 ppm (av. 15 ppm) (Radtke *et al.,* 1972*a*; Harris and Radtke, 1976). The nature of the boron minerals is not stated. In the auriferous quartz-pebble conglomerates, tourmaline tends to be disseminated and relatively scarce except locally in the reefs. To some investigators the tourmaline in these deposits is detrital, to others introduced by hydrothermal action. The content of boron in these deposits rarely exceeds 150 ppm (Table 35).

In gold-quartz deposits tourmaline tends to be developed in the greatest amounts in the wall-rock alteration zones, particularly those immediately adjacent to the quartz veins or silicified zones. In some veins and silicified zones there is also frequently a development of disseminated crystals and sunbursts of tourmaline in the quartz; also in vugs and cross-cutting veinlets. This tourmaline and that in the wall-rock alteration zones generally carries a large number of trace elements, some present in considerable quantity. An example from the Ptarmigan Mine at Yellowknife will suffice to illustrate this point. This tourmaline contains enrichments of the following elements: Li – 23 ppm; Cs – 2 ppm; Zn – 1700 ppm; Cd – 31 ppm; Ga – 50 ppm; Ge – 5.4 ppm; As – 150 ppm; and Sn – 110 ppm.

The distribution of boron in the wall-rock alteration zones of some typical gold-quartz deposits is shown in Tables 44 to 59 inclusive. Enrichment with proximity to the veins is general and most marked in basic rocks (greenstones). Some veins in sedimentary rocks are marked by a zone enriched in boron, others show little, if any, concentration of the element near the veins.

The writer has not been able to trace the fate of boron during the oxidation of gold deposits with any degree of accuracy, mainly because its habit appears to be extremely erratic in the deposits that have been investigated. Tourmaline and most other boron silicates have a marked resistate tendency, although in places they alter to micaceous and other products, and boron is set free when subjected to supergene waters that have been percolating through sulphides and carbonates. At Keno Hill, where we have examined the fate of tourmaline in gold-quartz and lead-zinc silver veins, we have found that a considerable amount of the mineral passes into the resistates in the oxidized zones, then into the soils, and ultimately into the stream systems and placers of the area. Some boron, however, enters solution during oxidation processes and is carried away in the groundwaters and ultimately into the streams. This statement is supported by the presence of boron in small amounts in the underground waters and in some of the spring precipitates of the area (up to 50 ppm B). Much boron is, however, also retained in the oxidized zones particularly in limonite and wad (up to 5000 ppm B). The nature of this boron has not been characterized, although some of it is in tourmaline.

Boron exhibits remarkably little enrichment during oxidation of the disseminated (Carlin type) gold deposits. Radtke *et al.* (1972*a*) report 7 to 300 ppm B (av. 80 ppm) in the oxidized mineralized rocks ('oxidized ores') at Carlin, Nevada as compared with <7 to 200 ppm B (av. 70 ppm) in the mineralized carbonate rocks ('primary ores').

Tourmaline, and in places other resistant boron minerals, are common associates of gold in recent and ancient placers. The content of tourmaline varies widely, some of the mineral being contributed by the auriferous deposits and some coming from sediments, tourmaline granites and other boriferous rocks. The deposits in some places appear to be the main contributors (or contribute an excess of boron over the general background) since the pattern of the distribution of boron (mainly in tourmaline) in the stream sediments and placers is directly correlative with the abundance of gold in the stream sediments and placers and with the location of the gold veins.

Such patterns are clearly evident in the Dublin Gulch–Keno Hill area of Yukon as one can see by comparing the boron map published by Gleeson *et al.* (1968) and the map of gold in heavy concentrates of stream sediments by Boyle and Gleeson (1972).

Aluminum is a constant associate of gold in its deposits being present in the silicates of the wall rocks of deposits and in minerals such as sericite and feldspars in the veins and silicified zones and in the reefs of the quartz-pebble conglomerate type of deposit (pyrophyllite). The habit of aluminum during wall-rock alteration processes associated with gold deposits is discussed in the section on alteration.

Some gold-quartz deposits are marked by the development of alunite, $KAl_3(SO_4)_2(OH)_6$, the basic sulphate of aluminum, and occasionally also by the formation of aluminous minerals such as diaspore and gibbsite. Such deposits commonly occur in Tertiary acid and intermediate volcanic rocks, thought by some investigators to be altered by sulphuric acid solutions or vapours. The type deposits are at Goldfield, Nevada (Ransome, 1909) and the Kasuga Mine, southern Kyushu, Japan (Taneda and Mukaiyama, 1970). Other occurrences of this nature occur in Jurassic and Triassic lavas on Vancouver Island (Clapp, 1915) and elsewhere.

During the oxidation of gold deposits the aluminous minerals in the ore materials are generally highly altered and much of the aluminum is carried away especially where the solutions are highly acid or alkaline. Much alumina, however, remains behind, and the bulk of this is bound in the limonite and wad complexes. In some deposits abundant kaolinite and other aluminous clay mineral complexes are formed, and some aluminum enters supergene minerals such as scorodite and jarosite. In these deposits aluminum often exhibits an enrichment in the oxidized zones over that present in the primary ores. Alunite may also be formed in the oxidized zones where acid sulphate solutions derived from the oxidation of pyrite and other sulphides are widespread, and numerous other aluminum-iron sulphates such as alunogen and halotrichite may occur, but they are generally rare. Wavellite, the aluminum phosphate, is a notable mineral in the oxidized zones of some gold deposits. In some oxidized zones gold is notably concentrated in the highly aluminous parts particularly in kaolinite and in the aluminum-bearing jarosite and scorodite. Lindgren (1933) remarks on the enrichment of gold in kaolinized zones, Schwartz (1944) mentions rich gold concentrations in kaolin in the San Juan district of Colorado, and Petrovskaya (1955) states that kaolinite is a direct indicator of gold in the oxidized zones of some of the gold districts of eastern Transbaikal, U.S.S.R. The frequent occurrence of gold in scorodite and jarosite is noted in the section on gold in other minerals. Kaolin and minerals such as jarosite and scorodite appear to be avid precipitators of gold especially when in the colloidal form as noted in the section on gold in natural waters.

Gallium occurs only in the parts per million range in most gold deposits. It is concentrated principally in the aluminum silicates (sericite, pyrophyllite, etc.) and other aluminous minerals (up to 200 ppm) and in sphalerite (up to 4000 ppm) in which it evidently substitutes for aluminum and zinc respectively. These features have long been known and are reviewed in detail by Shaw (1957), Vlasov (1966–1968) and Borisenok (1970). According to the statistics provided by Ivanov and Meituv (1970) the average gallium content of sphalerite in lead-zinc deposits is highest (100 ppm) in low temperature (carbonate-barite-fluorite) deposits, from 3 to 35 ppm in medium temperature quartz-silicate-sulphide assemblages, and relatively low (7 ppm) in skarn deposits. Deposits in carbonate rocks are invariably enriched in gallium compared with other types of host rocks. Gallium also occurs in magnetite, pyrite, galena, chalcopyrite and tetrahedrite-tennantite but generally only in the range <10 to 100 ppm. This is the general range of the element in the pyrite of the gold ores of the Yellowknife district (Boyle, 1961*a*). In a sulphide millieu I have noted that gallium and cadmium have marked chemical similarities, and the two elements appear to have similar substitutional capacities in sulphides and sulphosalts. The ionic covalent radii of the two elements are respectively (Ga^{3+}, 0.62; Ga, 1.22) and (Cd^{2+}, 1.03; Cd, 1.49), and the considerable differences in size and change would seem to preclude the sympathetic replacement of the two elements in sulphide structures. The answer may, however, lie in the fact that in the sulphide GaS, gallium is not present as Ga^+ or Ga^{3+}, but is combined in Ga-Ga units in a layer lattice, each gallium atom being tetrahedrally co-ordinated by one Ga and three S atoms. Somewhat similar arrangements with tetrahedral co-ordination are found for Zn, Cd, Cu and S in sphalerite, wurtzite, greenockite and tetrahedrite-tennantite. Co-ordination number 4 predominates in sulphide structures containing Zn, Cd and Ga, and this appears to be the most energetically stable arrangement (the lowest free energy for the system). From this it follows that gallium and cadmium tend to show sympathetic substitutional habits in some sulphide systems. This explanation, however, does not apply to the frequent occurrence of Cd and Ga in galena in which the co-ordination number of the metal with sulphur is 6.

I have noted no particular coherence or correlation between gold and gallium in auriferous deposits nor has any been mentioned in the literature. The Tsumeb deposits of Namibia (Southwest Africa) appear to be particularly rich in gallium; a number of gallium sulphides such as gallite, $CuGaS_2$, occur there, but there is no marked enrichment of gold.

In the contact skarn copper deposits at Whitehorse, Yukon the magnetite in the magnetite-hematite-bornite chalcopyrite-chalcocite bodies is greatly enriched in gallium in amounts up to 600 ppm (Kindle, 1964). The gold content of these ores is low (0.005–0.135 oz Au/ton; the silver values are relatively high, up to 3.4 oz/ton).

Much of the gallium in the pyrite in the Yellowknife gold deposits appears to have come from the country rocks (Boyle, 1961*a*, p. 119). In the Keno Hill area, Yukon, increases in the content of gallium (and indium) were noted in the wall rocks as some of the lead-zinc veins (some containing gold) were approached. In other veins a depletion of gallium was noted in the altered zones near the veins (Boyle, 1965*a*).

Radtke *et al.* (1972*a*) found <2 to 15 ppm Ga in the 'primary ores' at Carlin, Nevada and <2 to 30 ppm in the 'oxidized ores', indicating a slight enrichment of the element during oxidation processes. The carbonate host rocks contained <2 to 15 ppm Ga.

The gallium content of the auriferous quartz-pebble conglomerates rarely exceeds 5 ppm (Table 35). Most of the gallium appears to be present in the sulphides although there is probably some in the aluminosilicates.

Gallium hydroxide, $Ga(OH)_3$, like that of aluminium, is amphoteric and the metal is soluble in acid and base to give $[Ga(H_2O)_6]^{3+}$ and gallate $[Ga(OH)_4]^-$, ions respectively. The aquo ions undergo ready hydrolysis and hydrated forms of gallia such as $GaO{\cdot}OH$ and $Ga(OH)_3$ are precipitated between about pH 4 and 9. Hydrous iron and manganese oxides and aluminum hydroxide and hydrated oxides coprecipitate and carry gallium. In these the gallium is probably present as the hydroxide (Razenkov and Galaktionova, 1962). During the oxidation of gold deposits gallium tends to migrate in acid or strongly alkaline solutions and may be largely removed from the deposits. Some remains behind, however, in the limonite, wad and aluminous complexes and hence may be concentrated to a moderate degree with gold in some gossans and oxidized zones. Gallium may also be enriched in the secondary sulphide zones of some deposits, although there are no extensive investigations on this aspect of the chemistry of the element. Its coprecipitation with secondary lead, zinc, and cadmium minerals such as anglesite, calamine, smithsonite and adamite also seems probable, but minerals of this type analyzed by Papish and Stilson (1930) showed no detectable Ga. Kulikova (1962*a*, 1964, 1966), however, found the element in small amounts in smithsonite (1–10 ppm) and hydrozincite (2–3 ppm) but none in hemimorphite. In sauconite, the secondary zinc clay mineral, the element was enriched (up to 1000 ppm). Only low amounts were found in supergene lead minerals (traces–50 ppm). The hydrous iron and manganese oxides (limonite wad) contained up to 44 ppm Ga.

From her extensive research on the fate of gallium during the oxidation of sulphide deposits Kulikova (1966) concluded that the element is impoverished in the oxidized zones and is generally dispersed, especially during the initial stages of oxidation when the solutions are acidic in character. She also concluded that the principal minerals that concentrate gallium (and indium) are the hydrous iron oxides (limonite). To generalize we can say that in this respect gallium behaves somewhat like gold, but in its general ease of dispersion during the oxidation of sulphide deposits it differs from the noble metal.

There are no extensive data on the occurrence of gallium in recent and ancient eluvial and alluvial gold placers. The writer has noted the presence of the element (up to 20 ppm) in the weathered clay material of the eluvial gold placers of Dublin Gulch, Yukon, and from this presumes that in placers gallium is mainly present in the aluminous complexes and clay minerals which these deposits usually contain. There are probably also traces of gallium in oxidized residuals of sphalerite, galena, etc. and in minerals such as magnetite in most placers. The cassiterite concentrate from the Dublin Gulch placer was found to contain up to 100 ppm Ga.

Indium is present in most gold deposits in the parts per million range where the ores contain sphalerite, galena, chalcopyrite, tetrahedrite-tennantite and tourmaline. In typical gold-quartz deposits where sulphides are minimal the indium contents are invariably much less than 1 ppm. In the Witwatersrand quartz-pebble conglomerates the indium content in all samples analyzed in the Geological Survey laboratories was less than 1 ppm (Table 35). The data given by Shaw (1957), Vlasov (1966–1968) and Kulikova (1966) in their reviews of the geochemistry of indium indicate the maximum contents of the element in the following minerals: sphalerite (7000 ppm), galena (22 ppm), chalcopyrite (1500 ppm) and tetrahedrite-tennantite (10 ppm). Pyrite and arsenopyrite tend to be low in indium, although Auger (1941) noted its presence in pyrite at Noranda, and Boorman and Abbott (1967) found 100 ppm and 50 ppm in pyrite and arsenopyrite respectively in the Mount Pleasant, New Brunswick tin ores. The pyrite in the Yellowknife gold deposits contains up to 10 ppm In (Boyle, 1961*a*). Wolframite, cassiterite and other tin minerals such as stannite tend to be enriched in indium (up to 1000 ppm in cassiterite), but these minerals are not generally found in gold deposits except in placers. Certain gold deposits in the far eastern part of U.S.S.R. are relatively rich in cassiterite, wolframite and tourmaline and are hence relatively enriched in indium (up to 10 ppm) (Meshcheryakov, 1963). Scheelite is said to contain some indium in places, but I did not detect the element in this mineral in the gold-quartz veins at Yellowknife.

Three independent indium minerals have been identified: indite, $FeIn_2S_4$; roquesite $CuInS_2$; and dzhalindite, $In(OH)_3$. The first was found in a cassiterite deposit in U.S.S.R., the second in a copper-tin deposit in France, and the third is an oxidation product found in an indium-rich deposit in U.S.S.R. All of these minerals are extremely rare and have not yet been identified in gold deposits.

I have noted no particular coherence or correlation between indium and gold in typical hypogene gold deposits, nor has any been reported in the literature. In this respect gold differs somewhat from silver, which frequently shows a geochemical affinity with indium in a number of deposits (Badalov, 1961). In the gold-bearing waters of the Taupo volcanic zone in New Zealand, Browne (1969) reports the indium content to be less than 0.00005 ppm. By contrast the thallium content is 0.01 ppm.

The oxide and hydroxide of indium are essentially basic yielding the $[In(H_2O)_6]^{3+}$ ion. A number of indium complexes in sulphate solutions are possible, including such species as $[InSO_4]^+$ and $[In(SO_4)_2]^-$. The indium aquo ions are readily hydrolyzed, and hydrous iron and manganese oxides and aluminum hydroxide and hydrous oxide coprecipitate and carry indium mainly as the hydroxide, $In(OH)_3$, or as a variety of basic salts. We should, therefore, expect that during the oxidation of indium-bearing sulphides in gold deposits that acidic solutions remove much indium and disperse it into the water regime of an area. Where neutralization of the solutions takes place the aquo ions of indium are hydrolyzed and largely coprecipitated in the wad, limonite and aluminous complexes of the gossans and oxidized zones. Basic salts such as beudantite and jarosite should also take up some indium. On passing downward some indium is probably also precipitated in the secondary sulphide zones. Secondary zinc and lead minerals such as calamine, smithsonite, cerussite, anglesite and bindheimite may also incorporate available indium. A perusal of the literature suggests that this does in fact occur. Prokopenko (1941) found indium in jarosite and cerussite, and Anderson

(1953) noted its presence in cerussite and pyromorphite. A series of studies on indium in the oxidized zones of polymetallic deposits have been published by Vishnevsky (1958) and Kulikova (1962*b*, 1964, 1966). In general they find that indium is largely dispersed during oxidation especially when the solutions are acid. In the oxidized zones some indium is retained by limonite and wad and by hydrocassiterite if it is present. An enrichment of indium may occur in beudantite (up to 25 ppm), plumbojarosite (up to 90 ppm) and in bindheimite (up to 5000 ppm) in some oxidized zones. Kulikova thinks that indium arsenate, $InAsO_4 \cdot H_2O$, may form in the presence of pentavalent arsenic in acid solutions and may be coprecipitated with bindheimite and beudantite.

The above suggests that gold and indium may be enriched together in some gossans; also in the deeper zones where secondary arsenates and antimonates are developed. At Keno Hill a slight enrichment of gold was noted in bindheimite, beudantite and scorodite, but relatively little indium was present in these minerals. This may be because most of the sphalerite in these deposits contains only small amounts of indium (<100 ppm).

There are no data on the presence of indium in gold placers. Presumably the element is present in traces, particularly in residuals of sphalerite, pyrite, etc. and in cassiterite where it is present.

Thallium is a trace constituent of most gold deposits containing sulphides and sulphosalts. According to Ivanov (1959) the largest amounts of thallium are concentrated in the gold-bearing polymetallic deposits containing abundant lead, zinc and copper sulphides and sulphosalts. These deposits contain on the average from 1 to 5 ppm Tl with some having contents ranging from 10 to 50 ppm. Ivanov also states that the sulphide minerals containing thallium are: galena (50–100 ppm) with the highest amounts, and lead sulphosalts, sphalerite, chalcopyrite, pyrite and marcasite (1–5 ppm) generally with the lowest amounts. In the Karamazar region of U.S.S.R. Badalov and Rabinovich (1966) found that tetrahedrite and chalcopyrite were the richest thallium minerals with up to 15 and 5.6 ppm respectively. In the alteration zones of these deposits and in others, thallium may also be concentrated in sericite and alteration feldspars but only in the parts per million range (Kurbanayev, 1966). This is a consequence of the close coherence of thallium and potassium (and rubidium) in nature and the well known fact that thallium as Tl^+ replaces K^+ in micas, feldspars and other potassium minerals. A review of these and other phenomena involving thallium is given by Shaw (1957), Vlasov (1966–1968), and Voskresenskaya (1967). A number of polymetallic deposits contain thallium minerals such as lorandite, $TlAsS_2$, vrbaite $Tl(As,Sb)_3S_5$, crookesite, $(Cu,Tl,Ag)_2Se$ and hutchinsonite, $(Pb,Tl)_2As_5S_9$. These are, however, rare in ores with a relatively high gold content, but lorandite has been identified in a few gold-quartz and disseminated-type deposits. In some polymetallic gold deposits enriched amounts of thallium have been noted in pyrite (up to 1000 ppm or more) and in other sulphides and sulphosalts.

Typical gold-quartz deposits appear to have very low contents of thallium, except those with an abundance of sulphides. I did not detect the element in the Yellowknife ores by spectrographic methods, and other gold-quartz deposits I have investigated in Canada have contents less than 1 ppm in the ores. The quartz-pebble conglomerates of the Witwatersrand have less than 1 ppm Tl according to my analyses (Table 35). Skarn-type gold deposits also appear to be relatively low in thallium except where they contain abundant lead, zinc and copper minerals. Even in these the contents are low according to Ivanov and Meituv (1970), who give a statistical average of 1 ppm Tl for such deposits.

My review of the literature on the occurrence of thallium and gold confirms the view of Ivanov (1959) and Ivanov and Meituv (1970) that thallium tends to be concentrated in medium and low temperature deposits. In this respect it is interesting to note that thallium is enriched in some present day gold-bearing precipitates from hot springs and drillhole discharges, as witnessed by the evidence given by Weissberg (1969), who found up to 5000 ppm Tl in red-orange amorphous sulphides with opaline silica in the Taupo volcanic zone of New Zealand. The alkaline waters of this zone contain up to 0.01 ppm Tl (Browne, 1969). The disseminated deposits (Carlin type) are somewhat enriched in thallium according to the data provided by Radtke *et al.* (1972*a*). Lorandite occurs in barite veins in some of the Carlin orebodies (Callahan, 1974). The mineral occurs intergrown with realgar, orpiment and an unknown Tl-Hg-As sulphide mineral. The orpiment is thallium-rich according to Radtke *et al.* (1974*a*). In the ores of the Getchell Mine, galkaite, $(Hg,Cu,Tl,Zn)(As,Sb)S_2$, has been identified by Botinelly *et al.* (1973), and in the ores of the Carlin deposit a new mineral carlinite, Tl_2S, has been described by Radtke and Dickson (1975). Carlinite occurs as small subhedral to anhedral grains with fine-grained quartz and hydrocarbon compounds in carbonaceous limestones in the east pit of the deposit. In contrast to these relatively low temperature types of deposits, fumarolic sublimates are relatively low in thallium according to the data compiled by White and Waring (1963). In those of Vesuvius the values range from not found to 10 ppm Tl, and those of Papandajan in Indonesia have 80 ppm Tl.

It is difficult to establish a direct coherence and correlation between thallium and gold in auriferous deposits, because no detailed study of this feature has been done. Having examined the literature carefully it is apparent that gold and thallium have a geochemical affinity or coherence in deposits with abundant Pb, Zn, As, Sb and Hg; in other deposits, particularly the gold-quartz and skarn-type the situation is less certain. By anology with silver, which exhibits a definite coherence with certain elements of the second long period of the periodic table, viz. Pd, Ag, Cd, In, Sn, Sb, we should expect that gold would show a marked coherence with thallium both of which are members of the third long period, viz. Pt, Au, Hg, Tl, Pb and Bi. Support for this view is found in the following: the oxidation states of both gold and thallium are the same, Au(I), Au(III); Tl(I), Tl(III), and the radii of the thallous and aurous ions are similar, Tl(I), 1.44Å; Au(I), 1.37Å. The thallous state is more stable in aqueous solutions than the thallic, and both are markedly stabilized in solutions by complexing (e.g., with Cl) in a manner analogous to the Au(I) and Au(III) states. Thallic and auric salts are quite similar in their chemical reactions. In general Tl(I) and Tl(III) are much more stable toward reducing compounds than the corresponding gold states, but the ions of both metals are precipitated by H_2S to yield the sulphides Tl_2S, Au_2S and Tl_2S_3. Thallous sulphide is relatively stable and its analogues occur in nature; thallic sulphide is a very unstable compound. Gold sulphides are markedly unstable, yielding the free metal readily. Brooks (1961) has noted a coherence between thallium and bismuth, and as explained later, gold also has a marked affinity for bismuth.

It should also be mentioned that thallium shows a marked coherence with silver and lead, a feature that has been remarked on by the writer in a previous publication on silver (Boyle, 1968*b*). The coherence between these three elements is a consequence of the chemical similarity of the precipitation of their sulphides and the chemistry of their complexes in solution. Their ionic radii are also similar, Tl(I), 1.44Å; Ag(I), 1.31Å; and Pb(II), 1.32Å.

Thallium occurs in two oxidation states (I) and (III). The latter probably does not occur in nature except where the oxidation potential is very high. Thallous hydroxide, TlOH, resembles the alkali metal hydroxides in being a soluble strong base. Thallic hydroxide, $Tl(OH)_3$, is purely basic. Thallous sulphate is moderately soluble in water; the halide is sparingly soluble. Thallium forms a number of soluble complexes in aqueous solutions; with chloride the complexes are of the type $[TlCl_6]^{3-}$. The thallous ion is not particularly sensitive to pH (like K^+), but the thallic ion is extensively hydrolyzed to $[TlOH]^{2+}$ and the colloidal hydrous oxide at a pH as low as 2. Thallic hydroxide and the hydrous oxide are extensively coprecipitated by limonite, wad and various natural alumina complexes; like K^+ the thallous ion is probably strongly adsorbed by clay minerals and other colloidal complexes.

With the above features in mind one can predict the fate of thallium during the oxidation of thallium-bearing gold deposits containing sulphides. Released from the sulphides and minerals like sericite thallium is probably largely in the Tl^+ state and under both acid and alkaline conditions would possess a relatively high mobility, much of the element being dispersed into the water regime of the area. Any thallic salts or complexes formed would be quickly hydrolyzed and coprecipitated with the limonite, wad and other oxidation products of the gossans and upper parts of oxidized zones of the deposits. Under such conditions one might expect an enrichment of both gold and thallium. More generally, however, the thallium as Tl^+ passes downward in solution where some is adsorbed and incorporated by the hydrous iron and manganese oxides, supergene clay minerals and particularly by basic salts, such as jarosite, containing K^+ and probably also by numerous supergene lead minerals such as cerussite, anglesite, beudantite, bindheimite, etc. In the supergene sulphide zones some thallium may also be precipitated with the various sulphides. Since gold is also precipitated in all of these zones during oxidation processes one might expect a sympathetic enrichment of the two metals.

Studies of the fate of thallium during the oxidation of deposits have produced mixed results. Ivanov (1959) states that in certain rich thallium-bearing deposits the highly oxidized zones are depleted in thallium compared with the primary ores, and that the greatest enrichments of the element occur in the zones of secondary sulphides, apparently mainly in pyrite and marcasite. Mogarovskii (1961) found thallium phenomenally enriched in jarosite (up to 2.04%). As limonite and other iron oxides succeed this basic salt, thallium tends to be strongly leached except where wad is formed. In this complex thallium tends to be enriched in psilomelane and pyrolusite. It may also form the independent mineral, avicennite, Tl_2O_3, under conditions of high oxidation potential. Kulikova (1962*a*, 1964) found that thallium was generally leached, especially during the acid stages of oxidation. During the later neutral and alkaline stages the element was retained in small amounts of wad, limonite and other supergene minerals. In the Maykain gold-barite polymetallic deposits, Kurbanayev (1966) found that much thallium was retained in the weathered products, particularly those derived from sericite. These various studies indicate that gold and thallium may concentrate together during oxidation especially where basic salts such as jarosite are formed and where considerable adsorption and/or coprecipitation by hydrous iron and manganese oxides and clay minerals takes places. Retention of much thallium in oxidized zones is suggested by the sporadic occurrence of the element in spring and mine waters in mineralized belts containing gold and polymetallic deposits. I did not find thallium (or indium) in the natural precipitates at spring orifices in the Keno Hill area, Yukon, and Borovitskii *et al.* (1966) found only sporadic concentrations of the element in amounts up to 1 ppb in the mine waters of the gold regions in the Aldan region, U.S.S.R.

There are few data on the thallium content of recent and ancient eluvial and alluvial placers. Presumably the element is present in exceedingly low amounts in these deposits being present probably only as traces to minor amounts in oxidized residuals of galena, sphalerite, etc.; also in clay minerals. The last seem to be important concentrators in places since Kurbanayev (1966) found that the eluvium and alluvium derived from the weathering of sericite contained more thallium (av. 0.1 ppm) than the bedrock (av. 0.02 ppm) containing the Maykain gold-barite polymetallic deposit.

Group IIIB: Sc, Y, La, Ce and other rare-earths, Th, U

Scandium appears to be a relatively constant associate of gold in its deposits judging from the work done on the element in the Yellowknife district. There, scandium appears in amounts ranging from 10 to 100 ppm in the tourmaline in vein quartz and wall rocks in greywacke and slate; also in about the same amounts in late carbonates (mainly calcite) in the quartz and silicified bodies in greenstones. I did not detect it in scheelite or other minerals in the deposits. I have noted the presence of scandium in other gold deposits at Red Lake where the element occurs mainly in tourmaline in amounts up to 50 ppm. These values are not much different from what I find in the tourmaline of pegmatites at Bernic Lake, Manitoba and Buckingham, Quebec (100 and 30 ppm Sc respectively). There is probably also a slight enrichment of scandium in auriferous skarn deposits that are relatively rich in W, Sn, Mo and rare-earths. Auriferous deposits carrying uranium also seem to be slightly enriched in scandium in places. In the Carlin disseminated deposits Radtke *et al.* (1972*a*) report an average of 8 ppm Sc in the 'primary ores' and 10 ppm Sc in the 'oxidized ores'. The carbonate host rocks contained an average of 3 ppm Sc. In the uraniferous conglomerates at Elliot Lake the scandium content averages about 10 ppm. In the quartz-pebble conglomerates of the Witwatersrand the scandium contents range from 0.7 to 16 ppm. There is no relationship between the uranium and scandium contents of the ore in either deposits (Table 35).

In most gold deposits there is invariably some scandium in the wall-rock alteration zones usually in tourmaline, apatite and carbonates; the habit with respect to proximity to gold ore, is commonly erratic, but in some places there is a slight increase as ore is approached (Tables 44–59 inclusive).

According to the literature on scandium in hypogene mineral deposits, the element is concentrated principally in deposits enriched in tungsten, niobium, tin, zirconium, rare-earths, beryllium and uranium, principally in pegmatites, greisen veins, skarn and carbonatites (Shcherbina, 1960; Borisenko, 1961; Park, 1966; Vlasov, 1966–1968; Frondel and Ito, 1967). There is no mention of enrichments of scandium in gold (and silver) deposits in these reviews, and no instance of any concentration of scandium minerals in typical gold deposits could be found in the world literature. The principal minerals carrying scandium in the above mentioned deposits are wolframite, cassiterite and a great variety of rare-earth minerals such as euxenite, xenotime, allanite, etc. The scandium minerals thortveitite and sterrettite are very rare. In ferromagnesium silicates and other minerals, Frondel and Ito (1967) find that scandium largely replaces Al and Fe in the 6-co-ordinated (Al, Fe^{3+}) positions.

Scandium is exclusively trivalent in nature and its solution chemistry is similar to that of the rare-earths and aluminum, but its oxide is decidedly more basic than the latter but less so than the oxides of the rare-earths. The scandium ion, being smaller, has a greater tendency to hydrolyze than the rare-earth ions, and complex formation is more pronounced. In alkaline carbonate solutions soluble complexes of the type $[Sc(CO_3)_4]^{5-}$ are stable. Scandium forms a hydrous oxide, $Sc_2O_3 \cdot nH_2O$, and a definite hydrated oxide, ScO(OH), similar in structure to AlO(OH). The oxide is amphoteric. The sulphate is soluble; the phosphate, carbonate and fluoride, like those of the rare-earths, are insoluble. Hydrous iron and manganese oxides and aluminum hydroxides adsorb and/or coprecipitate scandium to a marked degree.

Relatively little is known about the fate of scandium during the oxidation of gold deposits. As might be expected from the above summary of its solution chemistry, scandium tends to be slightly concentrated in limonite and wad and in aluminous clay minerals. At Keno Hill I found scandium contents ranging from 10 to 100 ppm in some of these materials. One might expect some concentration of scandium in supergene carbonates and phosphates, but this was not found at Keno Hill, probably because of the large amount of sulphate in the waters that renders the element highly soluble. In general, it is probable that scandium is largely leached from deposits during oxidation processes, especially where the waters are acidic in nature. This was the conclusion of Kalenov (1958) regarding wolframite and allanite deposits. In this respect scandium tends to follow calcium, strontium and the rare-earths.

Scandium is present as traces in recent and ancient gold placers mainly in cassiterite, monazite, wolframite, baddeleyite, allanite, other resistant rare-earth minerals, and probably in wad, limonite and the clay complexes. Its presence in placers, together with gold, is therefore, largely incidental and dependent mainly on the occurrence of scandium-bearing resistate minerals.

Yttrium, lanthanum, cerium and the other *rare-earths* appear to have a fairly widespread distribution in gold deposits of all types and exhibit slight enrichments in some skarn and quartz-pebble conglomerate deposits. There is a vast literature (Ginzburg *et al.,* 1959; Vlasov, 1966–1968) on the rare-earths, very little of which pertains to gold deposits. I have, however, investigated the distribution of yttrium, lanthanum and the rare-earths in a semiquantitative way in a number of types of gold deposits from which some general conclusions can be drawn.

In auriferous skarn deposits yttrium, lanthanum and the various other rare-earths are bound in carbonates, garnet, sphene, epidote, apatite, allanite, monazite, brannerite, uraninite, fluorite and scheelite. Excepting the carbonates, garnet and epidote these minerals are relatively minor in amount, and as a whole most skarns generally only contain from 10 to 100 ppm total rare-earths. There appears to be no particular relationship between gold and yttrium, lanthanum and the rare-earths in skarns, but the problem requires more detailed study than I have been able to devote to it.

Recently we have noted native gold in brannerite in the tourmaliniferous skarn at the Richardson Mine, Eldorado, Ontario (Steacy *et al.,* 1974*a,b*). The native gold is later than the brannerite and may belong to a different period of mineralization.

In gold-quartz deposits there is a slight but often erratic enrichment of yttrium, lanthanum and the other rare-earths in the wall-rock alteration zones. The enrichment tends to follow the calcium content and appears to be largely dependent on the abundance of calcium-bearing carbonates. In the quartz bodies yttrium, lanthanum and the other rare-earths prefer the carbonates with a high calcium content and are, therefore, generally enriched in the younger carbonates in the deposits. The older carbonates such as ankerite tend to contain only low amounts of yttrium, lanthanum and the other rare-earths (<10 ppm) whereas the young calcite, especially if well crystallized may contain up to 500 ppm of these elements. The general enrichment of the yttrium earth group of metals in the carbonates (Boyle, 1961*a*), in contrast to low and erratic contents of the cerium earth group, is probably due to the easier capture of the yttrium earths to replace Ca^{2+} because of the closer similarity in radii as shown below.

Ca^{2+} – 0.99Å
Y^{3+} – 0.92Å
Yb^{2+} – 1.03Å
Ce^{3+} – 1.07Å
La^{3+} – 1.07Å

Some gold-quartz and polymetallic deposits carrying gold may be enriched in yttrium, lanthanum and the other rare-earths mainly in minerals such as uraninite, brannerite and thucholite. Examples of these deposits are present in the Goldfields area of Saskatchewan (Robinson, 1955) and in the Cluff Lake deposit in the Carswell structure, Saskatchewan (Little *et al.,* 1972), where native gold occurs in complexly mineralized veins containing pitchblende, uraninite, clausthalite, Ni-Co arsenides and thucholite; in the La Gardette (Isère) area of France (Geffroy, 1963) where brannerite occurs in the gold veins; and at the Little Nell occurrence Plumas County, California where brannerite is also present with gold in the veins and in fractures in an albitite dyke (Pabst and Stinson, 1960). Jouravsky (1952*b*) also mentions the association of brannerite with gold and molybdenite in the Ni-Co arsenide deposits of Bou-Azzer in Morocco. The bastnaesite deposits at Mountain Pass, San Bernardino County, California are apparently not enriched in gold, but auriferous sulphides occur in the immediate vicinity of these deposits (Sulphide Queen Mine) (Olson *et al.,* 1954). The Sulphide Queen orebody apparently contained some rare-earth carbonate and thorium-bearing minerals.

Aleksandrov *et al.* (1975) noted the presence of thorian florencite, Ce $Al_3(PO_4)_2(OH)_6$, in the carbonate-sulphide alteration zones of the Bodaibo deposits, eastern Siberia. They considered the mineral to be an indicator for gold mineralization in the deposits.

Radtke *et al.* (1972*a*) detected a general enrichment of Ce, La, Y and Yb in the 'primary ores' at Carlin, Nevada compared with the host carbonate rocks. The 'oxidized ores' also show a slight enrichment of these elements compared with the 'primary ores' when the averages are considered.

Auriferous quartz-pebble conglomerates and associated quartzites, etc. (Witwatersrand type) are frequently enriched in rare-earths and particularly in yttrium and lanthanum (Table 35). Minerals containing these elements in the deposits include principally brannerite, uraninite, zircon, allanite and thucolite. Brannerite is the most common rare-earth (mainly Y) mineral in the Elliot Lake–Blind River deposits. In the Rand, uraninite carries the bulk of the rare-earths; other rare-earth–bearing minerals include monazite, betafite, euxenite, brannerite and uranothorite. The rare-earth–bearing mineral in the Jacobina, Brazil conglomerates appears to be uraninite, although uncertainties about this (Gross, 1968) make one wonder if brannerite or some other such mineral is not present.

The relationship between gold, yttrium, lanthanum and the other rare-earths (also U and Th) in the quartz-pebble conglomerate type of deposit is not entirely clear. Gold and these elements may be cogenetic although there has been much dispute and discussion about this point, the gist of which is reviewed in the section on these deposits in this chapter. In the Rand, Liebenberg (1955), in a classic study, found a general sympathetic relationship between gold and uranium (and hence probably between gold and rare-earths). This led him to conclude that the gold and uraninite were deposited simultaneously regardless of their ultimate origin.

Uranium (actually the radioactivity) and gold also vary sympathetically in a number of conglomerate beds in the Jacobina deposits (Gross, 1968). This probably means that rare-earths and gold also vary sympathetically since uranium and rare-earths are invariably associated in such deposits. A number of economic gold-bearing conglomerates in the Jacobina area are, however, virtually barren of radioactivity, a feature that has led Gross (1968) to conclude that there is no reason to assume that gold and uranium are cogenetic.

Sulphide-rich parts of the Blind River–Elliot Lake conglomerates are enriched in gold and in many cases in uraninite and brannerite and hence in yttrium and rare-earths. It is not known, however, how gold (and silver) vary overall with yttrium and the rare-earths within the deposits because few gold analyses with this purpose in mind have been done.

The solution chemistry of yttrium, lanthanum and the rare-earths is relatively simple in general, but somewhat complex when each of the elements is considered in detail. The oxidation state for most of these elements is 3, and the ions tend to be relatively mobile especially where the waters are acid and abundant sulphate is present in the solutions. All of the rare-earths and yttrium and lanthanum form oxides of the type M_2O_3. The hydroxides, $M(OH)_3$, are definite compounds, and their basicity decreases with increasing atomic number as their ionic radii decrease. The hydroxides are not amphoteric. The fluorides are insoluble as are also the carbonates and phosphates. In alkaline carbonate solutions soluble complexes of the type $[M^{3+}(CO_3)_3]^{3-}$ are stable. Cerium can exist in the Ce^{4+} state in natural aqueous solutions under conditions of a high oxidation potential. Its aqueous chemistry is similar to zirconium, hafnium and the quadrivalent actinides. Except at very low pH (<1) hydrolysis and polymerization of ceric ion, $[Ce(H_2O)]^{4+}$, is extensive. A number of the rare-earths can also exist in the $+2$ state of oxidation. Their aqueous chemistry is similar to barium although there are some major differences. The pH of hydrolysis of the various ions of the rare-earths and yttrium show considerable spread from about 2 for Ce^{4+} to 8 for La^{3+}. Because of this they tend to be separated in supergene processes, but the details are complex and not well understood.

Not much is known about the fate of yttrium, lanthanum and the other rare-earths during the oxidation of gold-quartz deposits. My general studies indicate that the elements are relatively mobile and are largely leached in deposits where the strong oxidation of pyrite gives acid sulphate solutions. Small amounts of most of the rare-earth elements and yttrium are, however, retained in the wad and limonite and secondary carbonates. Supergene phosphates such as pyromorphite may collect the rare-earths as I have found at Keno Hill. With increasing neutralization of the solutions hydrolysis phenomena apparently lead to coprecipitation of many of the rare-earths in limonite and secondary carbonates. Under alkaline conditions it seems probable that yttrium, lanthanum and the other rare-earths have considerable mobility in complex forms, particularly as the relatively stable $[M^{3+}(CO_3)_3]^{3+}$ ion as Krainov and Loginova (1968) have suggested.

There are no detailed studies of the fate of the rare-earths during the oxidation of pyritiferous gold-bearing conglomerates. In the near-surface parts of the deposits at Blind River and Elliot Lake acid conditions prevail because of the formation of sulphates and sulphuric acid derived from the oxidation of pyrite. Uranium and thorium are partly leached and dispersed, and yttrium, lanthanum and the other rare-earths appear to suffer the same fate although small amounts are retained in the limonite and other oxidation products. Gold appears to be more abundant in the oxidized parts of the outcrops than in the primary ore, but the writer's work is too limited to indicate that this is the general case. If an enrichment of gold is a general one as I suspect it is, it would appear that yttrium, lanthanum and the other rare-earths part company with gold during the oxidation of pyritiferous conglomerates, the gold remaining behind and yttrium, lanthanum and the other rare-earths moving downward or being dispersed in the groundwaters.

Yttrium, lanthanum and the rare-earths invariably accompany gold in eluvial and alluvial placers, being concentrated mainly in monazite, allanite, zircon, scheelite and a number of other rare-earth–bearing resistate minerals. Most of these minerals come from the country rocks. The association of gold with yttrium, lanthanum and the other rare-earths in placers is, therefore, largely incidental, being predicated on the fact that gold and some of the rare-earth–bearing minerals have a relatively high specific gravity and resistance to weathering and comminution during the formation of placers.

Uranium and *thorium* are infrequent associates of gold in its deposits, although the association is marked in the world's largest deposits, namely the pyritiferous quartz-pebble conglomerate (Rand) type. Some uranium is found in a few gold-quartz deposits, and both uranium and thorium may accompany gold in skarn type deposits, but generally only in traces and minor amounts.

Uranium and thorium are relatively rare elements in gold-quartz deposits in Canada. Most analyses of the ores of these deposits show only a few parts per million (generally <5 ppm) combined uranium and thorium. An exception to this is the Box Mine in the Beaverlodge area of Saskatchewan where Geological Survey analyses show from 5 to 55 ppm U and 20 to 34 ppm Th in the wall rocks and mineralized zones. The gold-bearing polymetallic deposits are, likewise, devoid of any concentration of uranium and thorium in Canada with the exceptions of the Opemiska Copper Mine in Quebec, the Consolidated Nicholson Mine in the Beaverlodge area of Saskatchewan where pitchblende and uraninite occur (Lang *et al.,* 1962), and the unusual auriferous uranium deposits at Cluff Lake in the Carswell structure, Saskatchewan where native gold and gold tellurides are associated with abundant pitchblende, uraninite, clausthalite, chalcopyrite and Ni-Co sulpharsenides (Little *et al.,* 1972). Digenite also occurs abundantly in parts of these deposits.

In foreign deposits uranium and thorium are encountered in relatively few gold-quartz and polymetallic deposits. The veins of the La Gardette (Isère) district in France contain some brannerite (Geffroy, 1963) and those of the Little Nell Mine in Plumas County, California carry the same mineral in small amounts (Pabst and Stinson, 1960). In some veins from Guadalupe, Chihuahua, Mexico, uraninite and gold are associated (Krieger and Hagner, 1943). In some of the Tertiary cupriferous veins of Mitterberg, Salzburg, Austria, gold occurs in nodules of brannerite and uraninite associated in places with organic matter (Bernhard, 1966; Bauer and Schermann, 1971; Siegl, 1972; Paar, 1976). The gold is a late mineral in these deposits ramifying through the uraniferous nodules. Pitchblende accompanies gold in some of the Tertiary auriferous quartz veins and stockworks in the Central City district of Colorado. The pitchblende is an early mineral in the paragenesis of the veins (Sims *et al.,* 1963).

A study of the distribution of gold-quartz and gold-bearing polymetallic deposits in Canada suggests that these deposits only contain concentrations of uranium and thorium in metallogenic provinces characterized by the two actinide elements (viz. Box Mine, Nicholson Mine and Cluff Lake deposits in the Athabasca U-Th province). Similar conditions probably prevail in other parts of the world, but the data are too scanty to draw adequate conclusions. The exact relationships (paragenesis) of gold and uranium in the Nicholson, Box and Cluff Lake deposits are uncertain. In the Nicholson, where carbonates, nickel-cobalt arsenides, pyrite, chalcopyrite, galena, tiemannite, dyscrasite etc. occur, some of the gold may be cogenetic with the uranium, but some of the gold is definitely later than the pitchblende and thucholite (Robinson, 1955); in the Box the pitchblende appears to be related to a later stage of mineralization not necessarily connected with the gold.

Gold-bearing skarn-type deposits may contain traces to minor amounts of uranium and thorium, present mainly in minerals like apatite, monazite, zircon and allanite; uraninite and similar U-Th minerals are rare in most of these deposits. In the Keno Hill area we noted only 1.6 to 4.5 ppm U in sulphide-scheelite skarns containing up to 0.10 oz Au/ton. The uranium appears to vary directly with the tungsten content. In the Eastern Ontario gold belt, however, uranium-thorium minerals, including uraninite, brannerite and thucholite, occur in some quantity in the gold-bearing tourmaliniferous skarn zone at the Richardson Mine near Eldorado. In some samples from this deposit gold is later than the uraninite and brannerite; in other samples the gold is disseminated through the thucholite in a manner such as to suggest exsolution from a hydrocarbon gel (Boyle and Steacy, 1973; Steacy *et al.,* 1973, 1974*a,b*).

Many of the pyritiferous gold-bearing quartz-pebble conglomerate deposits are characterized by enrichments of uranium and in places by thorium (and rare-earths). These elements occur principally in uraninite, pitchblende and brannerite; also in smaller amounts in thucholite (or uraniferous carbon), uranothorite, betafite, euxenite, monazite, zircon and similar minerals. Details of these deposits and speculations on their origin are considered at greater length in a later part of this chapter.

The relationships between gold and uranium and thorium in the quartz-pebble conglomerate type of deposit are not entirely clear. The three elements may be cogenetic although there has been much controversy about this point. In the Rand deposits, Liebenberg (1955), after an extensive investigation, found that the uranium and gold contents varied sympathetically in the majority of the reefs and concluded that gold and uraninite, the principal U-Th mineral, were deposited simultaneously, regardless of their ultimate origin. In a later study Von Rahden and Urli (1969) showed statistically that there is a strong sympathetic relation and a high correlation between gold and uranium in a number of the reefs. In the volume edited by Haughton (1964*a*) on the Rand there is agreement among a number of authors that gold and uranium exhibit a sympathetic relationship. In the Virginia section of the Orange Free State Goldfield, Winter (*in* Haughton 1964*a*), however, states that while the uranium values follow the trend of gold values, the relationship varies widely and is very erratic. Feather and Koen (1975), summarizing the relationship between gold and uranium in the Rand, state that some investigators find a strong correlation between the two elements, others only a low degree of positive correlation, and a few no correlation at all.

Some sulphide-rich parts of the Elliot Lake–Blind River conglomerates are slightly enriched in gold and in many cases in uraninite and brannerite. It is not known, however, how gold (and silver) vary overall with uranium and thorium within the deposits because few gold analyses with this purpose in mind have been done. Lang *et al.* (1962) state that in general high uranium contents are related to abundant pyrite. Since the latter appears to carry or is associated with most of the gold (and silver) (*see* Table 11) a positive correlation between U, Th, Au and Ag seems probable.

In the Jacobina conglomerates in Brazil, Gross (1968) found that the radioactivity tends to increase with the gold content, this relationship being particularly obvious for samples containing either very high or very low quantities of gold. However, there are a number of economic gold-bearing conglomerates in the Jacobina area that are virtually barren of radioactivity, a feature that has prompted Gross (1968) to conclude that there is no reason to assume that gold and uranium are cogenetic.

Certain uranium deposits may be enriched in gold. The Jabiluka deposits in Northern Territory, Australia contain significant gold values (15 ppm), which can be won when the deposits are mined (Rowntree and Mosher, *in* Knight, 1975). These deposits occur in fractured and crushed zones in Lower Proterozoic metasediments of the Koolpin and Fisher Creek formations invaded in places by granitic pegmatites. The mineralization, including pitchblende and uraninite with some pyrite, chalcopyrite, chalcocite, covellite, galena and native gold, is most intense where the rocks are chloritized and hematitized. The gold is late and is associated with tellurobismuthite and tellurides, mainly altaite and melonite. The Cluff Lake deposits in Saskatchewan, referred to above, also contain significant gold values. Most of the uranium deposits that are enriched in gold appear to be of Lower Proterozoic age. In this respect it is of interest to note that some of the auriferous magnetite bodies in Lower Proterozoic rocks at Tennant Creek, Northern Territory, Australia have a uraniferous halo which ranges in magnitude from 20 to 280 ppm U (Large, 1975). In the writer's experience this is not unusual for many Proterozoic gold deposits, especially those in sedimentary terranes.

The oxidation of uranium deposits has been investigated intensively, and most of the supergene features of the element are well known. Much less is known about the fate of thorium, and there appears to be no extensive studies of the oxidation phenomena in gold deposits containing uranium and thorium, particularly the quartz-pebble conglomerate type.

In aqueous solutions the thorium ion Th^{4+} is extensively hydrolyzed at pH higher than 2.5; the resultant soluble species are numerous complexes depending on the nature of the anions, their concentrations, etc. The sulphate and the nitrate are soluble in acid solutions, and the complex ion $[Th(CO_3)_5]^{6-}$ is thought to be the principal species in alkaline carbonate solutions. The fluoride and phosphate are insoluble. In organic environments thorium is readily transported as thorium-humates or absorbed to (colloidal) humus. Thorium is strongly adsorbed and/or coprecipitated and carried by hydrous iron and manganese oxides, and various alumino-silicate gels probably as hydrous thoria, $ThO_2{\cdot}nH_2O$. The pH of precipitation of the hydroxide is about 6. Uranium differs from thorium in having two principal oxidation states in natural solutions, U(IV) and U(VI). The U(III) and U(V) states are also possible making the aqueous chemistry of uranium particularly intricate when it is realized that a veritable host of complexes and polymeric species are formed depending on the anions present, their concentration, etc. The ions of uranium are usually characterized as U^{3+}, U^{4+}, UO_2^{+} and UO_2^{2+}. The uranyl carbonate complexes $[UO_2(CO_3)_2]^{2-}$ and $[UO_2(CO_3)_3]^{4-}$ are probably the most important in natural alkaline waters. Uranium (IV) sulphate and nitrate are soluble; the phosphate, arsenate, molybdate and fluoride are insoluble, precipitates of these compounds being formed when U^{4+} ion is mixed with PO_4^{3-}, AsO_4^{3-}, MoO_4^{3-} and F^- in acid solutions. Uranyl (VI) sulphate and nitrate are soluble. In organic environments uranium is readily transported as uranium-humates or adsorbed to (colloidal) humus. A veritable host of supergene complex uranium (uranyl) minerals may form during the oxidation of uranium deposits, depending upon the presence of phosphate, molybdate, vanadate, silicate, carbonate, arsenate, selenite, tellurite and sulphate anions and cations such as Ca, Mg, Pb, Ba, Bi, Cu and K. Many of these appear to form by reaction with $UO_3{\cdot}H_2O$, the hydrous uranyl oxide gel, a hydrolysis product of uranyl ion. Solutions containing U^{4+} hydrolyze when neutralized, and the hydroxide $U(OH)_4$ or hydrous oxide $UO_2{\cdot}2H_2O$ is precipitated from which water can be split out to yield the oxide, UO_2 (uraninite). Alternatively, acidification of alkaline uranyl carbonate solutions yields the hydroxide $UO_2(OH)_2$ or hydrous oxide $UO_3{\cdot}H_2O$ from which uranium oxide (uraninite) may form by reduction. These reactions appear to be responsible for the occurrence of much supergene uranium black (uraninite). Finally uranium is adsorbed and/or precipitated and carried by hydrous iron and manganese oxides, silica-gels, etc.

With the above discussion in mind it is possible to predict the fate of Th, U and Au during the oxidation of deposits. Thorium is relatively immobile except under extremely acid conditions or when alkali carbonates are abundant in alkaline solutions. In these cases some thorium may be leached. More generally, however, considerable thorium is retained in the gossans as a result of adsorption and coprecipitation by limonite, etc., and the element is, therefore, enriched with gold. Supergene phosphates and a number of other minerals such as the arsenates may also retain much thorium. Under acid conditions uranium is extensively leached especially where pyrite is undergoing oxidation, the element being highly mobile as the sulphate. As the solutions are neutralized a great variety of supergene minerals may be formed, principally secondary uraninite and various phosphates, vanadates, carbonates, etc. Under alkaline conditions where the stable uranyl carbonate complex is formed uranium may be relatively mobile. Under most conditions where carbonates are minor gangue and wall-rock minerals, and where the deposits contain much pyrite as in the quartz-pebble conglomerates, uranium and gold tend to part company, the uranium being largely removed as the soluble sulphate from the oxidized zones and the gold remaining behind. Such phenomena appear to have taken place in some of the oxidized outcrops of the Blind River–Elliot Lake area.

Where abundant humic constituents are present in the surface waters and groundwaters U, Th and Au may be rendered mobile, and the three elements may be leached from deposits in which they occur. Alternatively, in gossans where humus and iron are strongly concentrated (humic limonite) Au may be enriched with U and Th evidently mainly as the result of adsorption phenomena.

Uranium and thorium are minor and trace elements in most recent and ancient alluvial and eluvial gold placers, but the presence of the elements with gold is largely incidental being predicated on the circumstances that gold and many of the uranium- and thorium-bearing minerals such as zircon, monazite and apatite, which derive mainly from the country rocks, are resistates.

Group IVA: C, Si, Ge, Sn, Pb

Carbon accompanies gold in all of its deposits being present as amorphous carbon, graphite, carbonaceous matter, various solid and semisolid hydrocarbons, and in a great variety of carbonates. The last are discussed in the next section on associated and host minerals of gold.

Black and grey quartz in gold-quartz deposits have long been recognized as a favourable indication of high gold values, and this is essentially true in many Precambrian gold belts in both sedimentary and volcanic terranes. In deposits in younger rocks, black and grey quartz are not particularly abundant except in some sedimentary terranes containing the familiar black slates or schists. Black carbonates may occur in the carbonated wall rocks or be intergrown with the black and grey quartz in some deposits, but they are relatively rare. Only in one or two deposits, in the writer's experience, have black carbonates been observed cutting older generations of black, grey and white quartz. The nature of the colouring of black and grey quartz is discussed at length in the next section on minerals associated with gold in its deposits. There, it is stated that the colouring is due mainly to amorphous carbon and graphite. The gold in black quartz may have been transported as an auriferous hydrocarbon the carbon and graphite being the polymerized residues of the hydrocarbon, or alternatively the gold may have been selectively precipitated from solutions or diffusion currents by the carbon or graphite.

Amorphous carbon and graphite accompany gold in some skarn deposits, but the relationships between the elements (C and Au) are not clear in most places. The carbon and graphite in some deposits appear to be residual from carbonate rocks after replacement by silicates; in others there is considerable evidence to suggest that the carbon minerals were deposited from some type of mobile carbon compound. It follows, therefore, that gold and carbon in skarn bodies may be associated as a result of the alternate processes suggested for their relationship in black quartz veins. Support for the transport of gold into skarn bodies as an auriferous hydrocarbon is found in the recent discovery of gold in thucholite in the Richardson Mine near Eldorado, Ontario. There, the gold appears as though it exsolved from a thucholite gel (Boyle and Steacy, 1973).

Carbonaceous matter, graphite and amorphous carbon in phyllites, slates and schists have long been regarded as favourable precipitants for gold and silver where they are in contact with or enclosed within veins, saddle reefs and silicified zones. These are the black leaders, beds or indicators of the old gold miners. In places, these indicators are phenomenally enriched in gold, some of which is difficult to extract by cyanidation. The reason for the enrichment is obviously the marked reducing action which the carbonaceous matter has on dissolved gold, a feature demonstrated long ago by Rickard (1896) with black bituminous Rico shale.

Carbon, bound mainly in authigenic thucholite (or uraniferous carbon) and what is called amorphous hydrocarbon (i.e., nongraphitic), is present in some quantity in the Rand conglomerates (Davidson and Bowie, 1951; Liebenberg, 1955). In the Blind River–Elliot Lake deposits thucholite is present mainly along slips and fractures. Some of the gold is intimately associated with thucholite in many of the Rand conglomerates, but the association is not always invariable. Liebenberg (1955) has concluded from his studies that some of the gold was deposited later than the thucolite, being in some cases moulded around the grains of the hydrocarbon, present as specks in the material, or in crosscutting veinlets and seams. In these cases the thucholite probably had a precipitating effect on the migrating gold. In the Black Reef, characterized in places by amorphous hydrocarbon, gold is not closely associated with this substance. According to Liebenberg (1955) this type of hydrocarbon was introduced at a later stage and did not affect the deposition of the (remobilized) gold.

Mention of 'carbon' frequently appears in the older literature on the Rand. For instance Graton (1930, p. 143) says "In those mines where it is at all common the 'carbon' is generally recognized, I believe, as the most significant and reliable of all indicators of good gold values." In a recent contribution on the carbon of the Rand, Hallbauer and van Warmelo (1974) have concluded that much of the thucholite represents fossilized plant (lichen) material. (*See* the further discussion on this finding in the section on the Rand in this chapter.)

On casual inspection the gold values in the Blind River–Elliot Lake conglomerates do not appear to bear any relationship to thucholite and other carbonaceous substances.

Thucholite and carburan are relatively rare in most gold-quartz-sulphide deposits, but examples are known in the auriferous Boliden ores of Sweden, in the gold-quartz ores of the Box Mine in the Uranium City district of Saskatchewan and in auriferous ores in other uraniferous belts.

Carbon and carbonaceous matter are common constituents of the disseminated type gold deposits, being particularly abundant in those in carbonate rocks as at Carlin, Nevada. Radtke and Scheiner (1970*a,b*) consider that the carbonaceous matter at Carlin and Cortez played a large part in the precipitation of the gold from acid hydrothermal solutions. Subsequent oxidation of the gold-organic complexes so formed precipitated the gold in a microscopic form. Wells (1971) on the other hand, using electron microprobe methods, noted no particular association of gold with carbonaceous matter in these deposits, but a close relationship to arseniferous minerals such as pyrite was found.

Silicon: 'Quartz is the mother of gold', so has run the prospector's adage since the time of Pliny and probably before. It is axiomatic to say that there is no hypogene gold deposit (including the conglomerate type) from which quartz in one form or another is absent. The correlative that all quartz veins or silicified zones contain economic quantities of gold is, however, not true, although the writer has not seen a quartz vein which on analysis does not contain a slightly higher amount of gold than that present in normal rocks (0.004 ppm).

On a statistical basis gold favours a quartz gangue whereas silver tends to occur in veins marked by a carbonate and/or barite gangue. These associations have been known for centuries, but the precise reasons for them have, however, escaped us to the present. The association of gold and silicon (silica) also extends to the plant kingdom as noted in the section on biogeochemistry. Such a marked relationship between gold and silicon must reflect some fundamental parallel in the chemistries of the two elements, either in their solution or colloidal characteristics. Further remarks on these phenomena are contained in the sections on gold in natural waters in Chapter II and on the origin of gold deposits in this chapter. The precise relationship of gold to quartz, chalcedony, silicification, etc., an important consideration in any study of gold, is reviewed in the next section on host and associated minerals. The chemistry of silica in the wall-rock alteration zones of gold deposits is discussed in the section on wall-rock alteration processes in this chapter.

The behaviour of silica during the oxidation of gold deposits is variable and complicated depending on the composition of the deposits and a number of other factors that are discussed in some detail in Chapter IV. Briefly, in some deposits quartz is particularly resistant to chemical attack and largely remains behind often with much gold in the rubble of the gossans and oxidized zones; in other deposits there is considerable solution and redeposition of silica in the gossans and oxidized zones; and in still others much silica is leached and dispersed into the groundwater systems. Generally speaking, gold and silica (quartz) often show a parallel behaviour during oxidation processes, due to two circumstances – their resistate nature and their solution and colloidal characteristics.

Quartz is a persistent mineral in gold placers. The 'white leads' of many placer fields and the 'white channel gravels' of others emphasize the importance of the mineral in these secondary deposits. Resistate silicates of many kinds also occur in all gold placers. They are listed and discussed in the section on placers.

Germanium is usually present in gold deposits containing chalcopyrite, tetrahedrite, enargite and magnetite, minerals that commonly contain from 5 to 50 ppm Ge. Higher values are found in cassiterite, stannite, topaz and in low temperature sphalerite (up to 3000 ppm); also in cinnabar (up to 2000 ppm or more), pyrargyrite and in the sulpho-germanates, germanite, renierite, argyrodite-canfieldite (up to 7% or more). All of these minerals, with the exception of sphalerite, are rare in gold deposits. In most gold deposits sphalerite is not noticeably germanium-bearing, containing only amounts up to 50 ppm according to the available data in the literature. Those we have investigated in gold deposits invariably contain less than 50 ppm Ge.

Reviews of the geochemistry of germanium can be found in the works by Fleischer and Harder (1955), Ginzburg *et al.* (1959) and Vlasov (1966).

Relatively little is known about the germanium content of skarns containing economic amounts of gold. In most of these bodies the element is present in low amounts (<50 ppm) according to the writer's investigations. Miroshnichenko *et al.* (1971) found amounts up to 90 ppm in rare metal and polymetallic skarns associated with granitic contacts in central Kazakhstan. Those near intermediate intrusives had lower contents. Skarn-greisen deposits were found to be especially rich in germanium, much of the element being present in topaz and muscovite (50 ppm each). All of the calc-silicates contained germanium, some garnets containing up to 180 ppm Ge.

In gold-quartz deposits with small amounts of sulphides the content of germanium is low, in the parts per million range or less; larger amounts can be expected in the pyritic, copper pyritic and polymetallic deposits where sphalerite and copper minerals are present. In the polymetallic deposits the contents may range up to 100 ppm judging from the literature. If bornite is present and germanium minerals are developed, some polymetallic deposits may contain up to 1000 ppm Ge or more in the ore. Fleischer and Harder (1955) mention that two gold mines in South Dakota produced concentrates, which contained 140 ppm Ge. Argyrodite has been identified in some of the silver-gold ores of the Hauraki goldfield, New Zealand (Ramsay and Kobe, 1974). There appear to be no extensive data on germanium in the Rand ores. Liebenberg (1955) reports only traces in the uraninite concentrates, and we found <2 ppm in suites of the ores (Table 35). In the Blind River–Elliott Lake ores the germanium content is <0.5 ppm.

There appears to be no particular relation between germanium and gold in its deposits, although the data are not extensive enough to substantiate this generalization in all cases. Germanium tends to be associated more with copper and silver than with gold, among the members of Group IB. The ores of the Tsumeb Mine in Namibia (South-West Africa), noted for their high germanium content, yield essentially Cu, Pb, Zn, Cd and Ag; the gold content is very low. Some germanium compounds (e.g., GeS) have a relatively high volatility, hence the low content of the element in deep, high temperature deposits. In near-surface (low temperature?) deposits a relationship between gold and germanium may exist. Two facts suggest this – the presence of argyrodite in the silver-gold ores of Great Barrier Island, Hauraki goldfield, New Zealand (Ramsay and Kobe, 1974) and a concentration of up to 0.004 ppm Ge in some of the thermal gold-bearing waters in the Taupo volcanic zone in New Zealand (Browne, 1969).

Germanium has oxidation states (II) and (IV). The (II) state is stable in nature where the oxidation potential is low and is probably the most important state in sulphides and some sulphosalts. In minerals like argyrodite, Ag_8GeS_6, however, germanium is apparently in the (IV) state. The quadrivalent state is stable under high oxidation potentials and is generally the state found in minerals in the supergene environment. The divalent state forms an amphoteric hydroxide characterized as $Ge(OH)_2$, although its exact nature is unknown. It may be a hydrous oxide of the type $GeO \cdot nH_2O$. The divalent hydroxide is readily oxidized in air to $GeO_2 \cdot nH_2O$ from which water can be split out to give GeO_2. This oxide is not markedly amphoteric, but Ge(IV) is soluble in acids such as HCl. The germanates are well characterized compounds forming the ions $[GeO(OH)_3]^-$, $[GeO_2(OH)_2]^{2-}$ and $[(Ge(OH)_4)_8(OH)_3]^{3-}$, as well as other more complex forms. It is probably in these forms that much of the germanium migrates in the supergene environment.

There are no data *per se* on the fate of germanium during the oxidation of gold deposits. Data in the literature on the transport of the element in natural waters and in sulphide deposits containing germanium, however, give the general outline (Frondel and Ito, 1957*b*; Ershov and Shcheglova, 1958; Pazenkova, 1967; Goleva and Vorob'yeva, 1967; Krainov, 1967; and Lyalikova and Kulikova, 1969). From these studies it is evident that germanium is relatively mobile under both acid and alkaline conditions. The forms of migration are speculative, but in acidic solutions it can be assumed that cationic complexes are present whereas in alkaline solutions the anionic complexes noted above are probably predominant. According to some investigators organic complexes are also important transfer agents. Bacteria aid the oxidation of sulphides containing germanium in both an acid and alkaline environment.

As initially released from sulphides germanium is probably largely in the (II) state; some released from minerals like argyrodite would be in the (IV) state. Where the oxidation potential is low germanium may migrate in the divalent state, but more generally this state is oxidized to the quadrivalent state, and germanium migrates largely as various germanate ions. In a milieu where abundant iron and manganese is present in solution, where hydrolysis phenomena are marked, and where limonite and wad are being precipitated, much germanium is absorbed and/or coprecipitated mainly in the limonite, perhaps as an iron germanate as Pazenkova (1967) has suggested. Passing downward through the gossans and oxidized zones some germanium as Ge(II) may substitute for Pb(II) in minerals such as anglesite, cerussite and a new basic lead sulphide, which Frondel and Ito (1957*b*) have described. Much germanium is, however, oxidized to the (IV) state, and some is taken up by various heavy metal arsenates such as bayldonite, mimetite, duftite, etc. where Ge(IV) is thought to substitute for As(V) in the (AsO_4) tetrahedra. Supergene minerals such as smithsonite, malachite, calcite, etc. contain relatively little germanium, but secondary silicates such as hemimorphite, the zinc silicate, may take up some germanium. Some germanium on reaching the secondary sulphide zone is incorporated in minerals such as chalcocite and covellite. The remainder is dispersed in the groundwater system, which may contain up to 1.5 ppb in the vicinity of sulphide and other deposits containing germanium.

We can see from the above outline that germanium and gold would tend to be concentrated together in various phases of the oxidation zones – in the oxide or gossan facies, in the basic salt and arsenate-sulphate facies, and in the secondary sulphide facies.

There are no data on the content of germanium in recent and ancient eluvial and alluvial gold placers. Presumably, the element is present as traces in these deposits, being present in limonite and wad particles, magnetite, garnet, cassiterite and in oxidized residuals of sphalerite, chalcopyrite and a variety of other minerals.

Tin is associated with gold in a number of its deposits but generally only in minor or trace amounts. The classic tin deposits are notably low in gold, and the reverse is also true that deposits enriched in gold seldom carry much tin; this despite the fact that both gold and tin deposits are marked by extensive silicification and the development of quartz, arsenic, antimony and bismuth minerals, tourmaline and other common mineral associates of gold. Silver on the other hand is commonly enriched with tin in a number of deposits, particularly those containing stannite and the rarer sulphosalts such as canfieldite, cylindrite, teallite, etc. An exception to these generalizations is found in the stanniferous provinces of the far eastern U.S.S.R. and other parts of eastern Asia; also in certain stanniferous regions in Australia (New South Wales, Tasmania). In the deposits of the far eastern U.S.S.R. Nekrasov (1973) emphasizes the fact that tin and gold minerals are not antagonistic. There, gold in two forms – native and dispersed in sulphides and arsenides – occurs in typical Au-Sn deposits. These are skarns with glaucodot-cobaltite, safflorite-loellingite and magnetite mineralization; quartz-gold-cassiterite and quartz-molybdenite-gold veins; and silicate-sulphide veins, stockworks and zones of greisenization mineralized with quartz, tourmaline, chlorite, arsenopyrite, pyrrhotite, scheelite, galena, sphalerite and gold. In all types the tin minerals are earlier than those containing gold.

Auriferous skarn deposits in most places contain only traces to minor amounts of tin, generally well below 50 ppm. Most of the tin is in the sulphides such as chalcopyrite, sphalerite, galena and various micas and the calc-silicates, probably largely as specks of cassiterite and other tin minerals. Well crystallized cassiterite, stannite and other tin minerals are relatively rare in the gold-bearing skarns of most mineralized belts.

In typical gold-quartz deposits tin invariably accompanies gold but only in trace amounts. At Yellowknife the gold ores in the greenstone belt carry less than 10 ppm Sn; at Kirkland Lake the range is 2 to 11 ppm Sn. Most of the tin at Yellowknife is present in stannite, which has been identified in polished sections. Traces (10–100 ppm) occur in pyrite, galena and sphalerite in most auriferous deposits. Gold veins and saddles in sedimentary rocks usually contain only traces of tin mainly in pyrite, galena and sphalerite. In the gold-quartz veins of the Balei mineralized belt U.S.S.R., Gapontsev and Polikarpochkin (1969) found tin to range from 2 to 30 ppm. In some ore shoots there was an upward increase in the tin content. In stanniferous regions throughout the world small amounts of cassiterite are common in auriferous veins as in New South Wales, Australia and in the Far Eastern tin belt of the U.S.S.R.

In the disseminated gold ores (Carlin type) only small amounts of tin are recorded (<7–20 ppm) (Radtke *et al.*, 1972*a*). There is no appreciable change with oxidation of these types of ores according to the available data.

Polymetallic deposits enriched in gold may carry higher amounts of tin than the typical gold-quartz deposits. In these deposits the tin may occur in stannite, canfieldite and other tin minerals, including minor amounts of cassiterite in places, but more generally the element occurs in amounts ranging from 10 to 1000 ppm in pyrite, chalcopyrite, galena, sphalerite and a variety of sulphosalts. The ores as a whole generally carry less than 100 ppm Sn.

Tin occurs only in traces in the auriferous quartz-pebble conglomerates (Table 35). Liebenberg (1955) described detrital cassiterite with a strong pleochroism from the Dominion Reef of the Rand. In most reefs only traces (3–6 ppm) of tin are present in the Rand ores according to our analyses.

During oxidation processes tin is relatively immobile due to the resistate nature of its oxide and the ease with which the element is precipitated from solution. Tin exists in two states of oxidation, (II) and (IV). The stannous state is probably not stable in nature except under a very low oxidation potential or when the ion is extensively complexed under very acid conditions. At the normal pH found in nature (5–8) stannous ion is readily oxidized by air giving stannic solutions. Stannous ion is, therefore, relatively rare in most supergene environments.

Stannic oxide or cassiterite, SnO_2 is amphoteric. The stannic ion in acid solutions is often characterized as Sn^{4+}, but this is a simplification since the ion is extensively hydrolyzed and complexed. Dilution or addition of base to a stannic solution leads to extensive hydrolysis and the precipitation of the hydrous oxide, $SnO_2 \cdot nH_2O$. From this water can be split out to give cassiterite. The oxide is soluble in excess base giving stannate ion usually written $[Sn(OH)_6]^{2-}$. Tin may, therefore, migrate in strongly acid and alkaline solutions in a cationic or anionic form respectively. Between pH 5 and 8 both forms are extensively hydrolyzed and the oxide is precipitated. Hydrous iron and manganese oxides (limonite and wad), the various silica-alumina gels (clay minerals), and hydrous titanium oxide coprecipitate, adsorb and carry tin in relatively large amounts.

In oxidizing zones cassiterite is relatively unaffected except under very acid and alkaline conditions when some tin may enter solution. More generally the cassiterite remains as a resistate in the gossans and oxidized zones, utlimately passing into eluvial and alluvial deposits. Stannite and the other sulphostannates on oxidation yield stannic or stannate ion to the solutions depending on the pH. These ions, however, have relatively little mobility – hydrolysis due to neutralization of the solutions or dilution precipitates the oxides as cassiterite (needle tin and wood tin). Coprecipitation and/or absorption of the soluble tin by limonite, wad and other gellike substances further restrict the mobility of the ions. Finally, much tin is captured and incorporated in a variety of basic salts and other supergene minerals precipitated during the various hydrolytic reactions in oxidation zones. At Keno Hill tin was found in anglesite (100–1000 ppm), smithonsite (200 ppm), beudantite (1000 ppm), bindheimite (100–1000 ppm) and jarosite (100–1000 ppm). Overall the lodes at Keno Hill showed relatively little change in their tin content with depth through the oxidized zones into the primary ore (Boyle, 1965*a*). In this respect the element behaved much the same as gold.

In some recent and ancient eluvial and alluvial placers, tin, mainly in the form of cassiterite, is concentrated with gold. Such placers, however, tend to be relatively rare, few tin placers containing economic concentrations of gold and vice versa. In some placers traces of tin accompany gold in the heavy concentrates. The element is present mainly in residuals of sphalerite, pyrite, galena, sphene, rutile and other common minerals that contain tin in primary deposits.

Lead is a universal associate of gold in all types of its deposits, the largest amounts being present in gold-bearing polymetallic and skarn deposits and the lowest in the gold-quartz and quartz-pebble conglomerate types. Galena is the principal lead mineral in all primary epigenetic gold deposits; some deposits carry appreciable amounts of various lead sulphosalts; and a few contain lead tellurides, selenides, bismuthides, etc. Tetrahedrite-tennantite, and various other sulphosalts, arsenides, sulphides and tellurides may contain minor to trace amounts of lead in gold deposits. The zoning relationships of lead with respect to gold are discussed in the last part of this chapter and shown in Figures 94 and 95.

Lead is present only in trace to minor amounts (up to 100 ppm in the ore) in some auriferous skarn deposits, particularly those marked by the presence of abundant copper sulphides or arsenopyrite (e.g., Nickel Plate and French mines, British Columbia). Other gold-bearing skarn deposits (e.g., New Calumet Mine, Quebec) contain considerable amounts of lead (up to 3%). There appears to be no particular correlation between the lead and gold contents in skarn deposits, although in some orebodies the lead-rich parts tend to be enriched in gold and particularly in silver.

Most gold-bearing polymetallic deposits are generally enriched in lead, but there appears to be no particular correlation between the gold and lead contents in these types of deposits in Canada according to the writer's investigations, which are, however, limited in their scope. Judging from the available data in the literature, correlations between the gold and lead contents in polymetallic deposits in other parts of the world appear to be weak or nonexistant, although further detailed research is desirable on this particular aspect of the geochemistry of gold.

The lead content of most gold-quartz deposits is low and often erratic. Deposits in Precambrian greenstones (meta-basalts, meta-andesites) and intermediate and acidic rocks generally contain less than 200 ppm Pb in the ore, mainly in galena. Higher amounts (up to 5000 ppm Pb) occur in some of these deposits (e.g., Yellowknife, Red Lake) where sulphosalts such as jamesonite are abundant in the ore. Some of the Tertiary gold-quartz ores in andesites and other volcanics are exceptionally rich in lead containing percentage amounts of the element. Gold-quartz deposits in sedimentary rocks of all ages tend to carry more lead than those in volcanic and other igneous rocks. The amounts of lead are highly variable in the deposits in sediments, ranging from mere traces to 2 per cent or more in the ore.

Schwartz (1944) mentions that galena is a particularly good indicator of high grade gold shoots in a relatively large number of gold-quartz and other types of auriferous deposits. He attributes this to the fact that galena and gold are frequently the last minerals in the paragentic sequence, and hence the two often occur together. In the writer's experience the presence of altaite, PbTe, commonly signals the presence of gold tellurides in deposits.

The lead content of the disseminated gold deposits (Carlin Type) ranges from <7 to 1500 ppm in the 'primary ores' and from <7 to 200 ppm in the 'oxidized ores' at Carlin according to Radtke *et al.* (1972*a*). The carbonate host rocks contain <7 to 15 ppm Pb.

Lead is a trace to minor constituent of the quartz-pebble conglomerate gold ores of the Rand. The content of lead in the ores appears to vary widely in sympathy with the abundance of galena. In local areas galena is abundant, but overall the lead content of the ores in samples analyzed at the Geological Survey ranges from 51 to 450 ppm (Table 35). This seems to agree relatively well with the analyses given by Saager (1969) who states that in the Basal Reef the chalcopyrite, galena and sphalerite on the average do not form more than 0.05 per cent of the total ore. Some of the lead is radiogenic occurring as specks and veinlets of galena in uraninite and thucholite. Ordinary (i.e., largely nonradiogenic lead-bearing) galena occurs throughout the reefs associated with pentlandite, pyrrhotite, sphalerite, chalcopyrite, cobaltite, linnaeite and arsenopyrite. This galena, characterized as secondary and pseudohydrothermal by Liebenberg (1955) and Saager (1969) respectively, occurs mainly interstitially in the matrix of the conglomerates where it replaces the matrix materials to a varying extent. Gold is apparently closely associated with galena and the other sulphides in some parts of the reefs, but Liebenberg (1955) concluded from mineragraphic work that most of the gold is genetically unrelated to the sulphide mineralization. The relationship of gold and lead (as well as elements in the various sulphides such as Zn, Co, Ni, Cu, As, etc.) in the Rand deposits is obviously complex as one can readily see by reading the various papers on the origin of these deposits. It would be interesting to investigate the detailed correlation of gold with these various chalcophile elements in the conglomerate orebodies. Such information could help in the solution of the origin of these controversial deposits.

Lead can exist in two oxidation states (II) (plumbous) and (IV) (plumbic). The plumbous compounds are prevailingly basic, and their salts ionize in solution. The plumbic compounds are few, are largely covalent, require the presence of high oxidation potentials, and are relatively unstable in natural situations. Only the plumbous compounds are important in nature forming the sulphide (PbS) and a variety of sulphosalts, tellurides, etc. in hypogene deposits. In the oxidized zones of lead deposits the most common plumbous minerals are the sulphate (anglesite), the carbonate (cerussite) and minerals like bindheimite (an antimonate), beaudantite (a basic sulphate) and pyromorphite-mimetite (a phosphate-arsenate).

Plumbous salts have a strong tendency to hydrolyze and form the insoluble hydroxide $Pb(OH)_2$ when base is added. This hydroxide is amphoteric dissolving in acid to give the plumbous ion and in excess base to form the plumbite ion $[Pb(OH)_3]^-$. The nitrate and acetate are soluble, the other plumbous salts such as the sulphate and carbonate are insoluble or only sparingly soluble. Soluble complexes of the type $[PbCl_3]^-$ are formed in the presence of excess chloride ion, and soluble carbonate complexes are stable in solutions enriched in CO_2 or hydrogen carbonates. Judging from our observations the soluble species of lead are relatively rare under most oxidizing conditions.

During the oxidation of gold deposits containing galena and sulphosalts, the lead is largely immobilized as the sulphate (anglesite) which in time is converted to the carbonate (cerussite) the most stable phase in oxidized zones. Some lead is also precipitated in the basic sulphate-arsenate, beudantite; in the pyroantimonate, bindheimite; in the phosphate-arsenate minerals, pyromorphite and mimetite; and in the basic sulphate, plumbojarosite. The oxide minerals, massicot, minium and plattnerite are rare in most oxidized zones. Supergene galena is also rare in most deposits. Limonite and manganese oxides in gossans tend to adsorb and/or coprecipitate considerable amounts of lead.

All of the supergene lead minerals are relatively insoluble especially under slightly acid and neutral conditions. At Keno Hill and in the vicinity of other lead deposits I have noted that only traces of lead (<0.005 ppm) migrate in the groundwaters (Boyle, 1965*a*). The general tendency, therefore, is for marked enrichments of lead to take place in the oxidized zones of deposits compared with the primary zones. In this respect gold and lead behave in a similar manner, and it is common to find both elements enriched in gossans and their underlying leached zones. In addition I have noted that a number of the supergene lead minerals in gossans and oxidized zones tend to adsorb, coprecipitate or otherwise accumulate gold. The following ranges in ppm for the gold content of supergene lead minerals from a number of gold-bearing deposits in Canada can be quoted: anglesite (0.01–0.5); cerussite and limonite (0.7); bindheimite (0.7); pyromorphite (0.17); cerussite (0.2); and beudantite (0.01–0.4).

Most recent and fossil eluvial and alluvial gold placers contain only traces of lead mainly in unoxidized residuals of galena and sulphosalts, and in minerals such as anglesite and cerussite. A few eluvial placers containing gold and silver may have relatively high contents of lead minerals. (*See* the section on gold in other products of weathering in Chapter II.)

Group IVB: Ti, Zr, Hf

These three elements show relatively little association with gold except in some placers.

Titanium accompanies gold mainly in minerals such as leucoxene, rutile, ilmenite, sphene and brannerite, in some skarn and gold-quartz deposits. The titanium in some of the minerals appears to represent an introduction of the element; in others the titanium minerals are residuals from alteration, or the element was derived from the wall rocks of the deposits. There appears to be no particular correlation between gold and titanium in these deposits according to the writer's investigations. Leucoxene (rutile, sphene, etc.) is a frequent alteration product in the alteration zones of some gold deposits, particularly those in basic and intermediate volcanic and intrusive rocks. The behaviour of titanium in these alteration zones is discussed in more detail in the section on alteration processes. For the association of brannerite with gold see the section on uranium and thorium.

The titanium content of the 'primary ores' at Carlin, Nevada ranges from 200 to 5000 ppm; in the 'oxidized ores', the range is 300 to 5000 ppm indicating no particular enrichment during oxidation of these gold ores (Radtke *et al.*, 1972*a*). The host rocks contain from 70 to 2000 ppm Ti, indicating an enrichment of titanium during primary mineralization.

Titanium, mainly in minerals such as leucoxene, rutile, sphene, ilmenite and brannerite, is a common minor and trace constituent of the quartz-pebble conglomerate deposits (Table 35). Some of the leucoxene in the Rand is radioactive (Liebenberg, 1955); brannerite is one of the principal uraniferous minerals in the Elliot Lake–Blind River ores. The relationship of titanium and titanium minerals to gold in the conglomerate deposits is uncertain. According to the placer theory, which is favoured by many, the minerals are mainly detrital, like the gold, but subsequently reconstituted or altered in part. Other ideas on the origin of these minerals in the quartz-pebble conglomerates are discussed later in this chapter.

Rutile, sphene, leucoxene, ilmenite and a variety of other titanium minerals accompany gold in recent and fossil eluvial and alluvial placers. Their association with gold in these deposits is mainly a consequence of their resistate character and high specific gravity. Brannerite occurs as a resistate mineral in the gold placers of Stanley Basin, Idaho.

Zirconium and *hafnium* exhibit no particular association with gold in hypogene deposits. Zirconium minerals are relatively rare in gold-bearing skarn deposits and in typical gold-quartz veins. Our analyses show only traces of zirconium in these deposits (<50 ppm). In the quartz-pebble conglomerate type of gold deposit zircon and a few other rarer zirconium-hafnium–bearing minerals are present in the matrix of the quartz conglomerate. Some of the zircons in the Rand are uraniferous (Liebenberg, 1955).The relationship of zircon and other zirconium-hafnium–bearing minerals to gold in the quartz-pebble conglomerate type of deposit is not clear. Some of the zircons may be detrital. The ores of the Rand contain from 47 to 320 ppm Zr (Table 35). Von Rahden and Urli (1969) noted a high correlation between Zr, Ti and Cr in some of the reefs in the Rand. Radtke *et al.* (1972*a*) record the following zirconium contents in the disseminated gold ores of Carlin, Nevada: carbonate host rocks – 30 to 150 ppm; 'primary ores' – 30 to 300 ppm; 'oxidized ores' – 30 to 500 ppm. Primary mineralization appears to have introduced some zirconium; oxidation has enriched the ores only slightly in the element.

Zircon commonly accompanies gold in recent and ancient eluvial and alluvial placers. Baddeleyite, ZrO_2, and the other rarer zirconium-hafnium–bearing minerals tend to be rare or of local occurrence in these deposits. All accompany gold as a consequence of their resistate character.

Group VA: N, P, As, Sb, Bi

Nitrogen exhibits no particular association with gold in any of its deposits. Phosphorus may accompany gold in some types of deposits. The other three elements in this group are closely associated with gold in many types of hypogene deposits.

Phosphorus, mainly in apatite, occurs in some gold deposits, principally in the skarn type but also in some gold-quartz veins. Hulin (1930) describes an occurrence of apatite as an important vein mineral in the Kennedy Mine of the Mother Lode district in California, and Schwartz (1944) states that apatite is present in a few other gold deposits. The writer has observed that apatite occurs in very minor amounts in most skarn and gold-quartz deposits, but there appears to be no particular correlation or association of phosphorus with gold in any of these deposits. In the Carlin, Nevada, disseminated gold ores Radtke *et al.* (1972*a*) report <0.01 to 0.5 per cent P in the 'primary ores' and 0.01 to 0.9 per cent in the 'oxidized ores' indicating some enrichment during oxidation processes. The carbonate host rocks contain <0.01 to 0.05 per cent P. In the quartz-pebble conglomerate type of gold deposit, apatite, monazite and some of the rarer phosphates occur sparingly in the matrix of the conglomerates. Geological Survey analyses show phosphorus contents ranging from 100 to 7500 ppm in the Witwatersrand ores (Table 35). Those recorded by Feather and Koen (1975) for the Rand show a range from <40 to 390 ppm P. There appears to be no particular association of phosphate minerals with gold in the conglomerate ores.

Smirnov and Entin (1975) have noted a bond between gold and phosphorus in a number of genetically diverse phosphatic deposits (magmatic, hydrothermal, sedimentary, etc.) in U.S.S.R. The contents of gold recorded in these deposits ranged from 0.0017 to 0.470 ppm with an average of 0.023 ppm. In certain apatite separates from the deposits up to 0.030 ppm Au was recorded. Smirnov and Entin point to the fact that the first three ionization potentials of gold and phosphorus are similar and suggest that complexation through sodium involving compounds of the type Na_3AuO_3 and Na_3PO_4 may be the reason for the bond between the two elements.

Supergene phosphates occur in some oxidized zones of gold deposits. Wavellite occurs in the oxidized parts of the veins at Cripple Creek, Colorado and elsewhere. Vivianite and ludlamite are also frequent accessory minerals in oxidized gold ores and may be primary in places. Pyromorphite-mimetite is common in gold deposits enriched in lead minerals. All of these phosphates originate by downward migration of soluble phosphate in the oxidized zones followed by precipitation where cations such as Fe, Al and Pb, bind the phosphate as insoluble minerals. Some gossans are relatively enriched in phosphorus due evidently to the strong adsorption and binding of phosphate by hydrous ferric oxides and wad. This was noted at Keno Hill and elsewhere in the oxidized zones of gold-quartz deposits. Unoxidized quartz-arsenopyrite gold ore in the No. 6 vein at Keno Hill contained 0.02 per cent P_2O_5 whereas the highly oxidized material ran 0.24 per cent P_2O_5 (Boyle, 1965*a*).

Because of their resistate character apatite, monazite and the rarer phosphates tend to occur in some abundance in gold placers of recent and fossil origin. My observations suggest that there is no particular relationship between the quantity of phosphate minerals and gold in placers, an anticipative circumstance considering that most of the phosphates are derived from the country rocks and not from the gold deposits.

Arsenic exhibits a nearly universal enrichment in most types of hypogene gold deposits, and there is a marked coherence between gold and arsenic during both hypogene and supergene processes. The most common arsenic minerals in hypogene gold deposits are arsenopyrite and tennantite-tetrahedrite. Other arsenic-bearing sulphosalts are common in certain deposits. Native arsenic is relatively uncommon, but occurs in relatively large amounts in some auriferous deposits, examples being the Engineer Gold Mine, Yukon (allemontite); Nagyág, Transylvania and Bau, Sarawak. Enargite is common in a number of the Japanese gold deposits; also in a few of the straight gold deposits and extensively in some of the copper deposits containing low gold values in the Cordillera of North and South America, in U.S.S.R., and elsewhere. Niccolite, cobaltite, gersdorffite, smaltite, safflorite and other Ni-Co-Fe arsenides are relatively rare in gold deposits, but a few gold-quartz veins and skarn deposits containing some of these minerals are known in Mexico; in the Middleburg district, northern Transvaal; in the French Mine, Hedley, British Columbia; in some of the gold deposits at Ramore, Ontario and elsewhere. The Ni-Co-Fe arsenide veins (Cobalt, Ontario type) with abundant native silver generally contain only traces of gold (<0.1 ppm). Hypogene orpiment and realgar appear to be rare in gold deposits, but the oxidized and secondary sulphide zones of some deposits may contain these minerals, usually in restricted amounts. Examples of the latter are found at Nagyág, in some Japanese deposits and elsewhere. Hypogene realgar and orpiment occur in the disseminated deposits of Carlin and Getchell in Nevada. When arsenic minerals are absent in gold deposits the element is largely camouflaged in pyrite or marcasite. Some average arsenic values for pyrite where arsenic minerals are rare or absent in the gold ore shoots of deposits, are given below:

Location	As in pyrite (ppm)
Keno Hill	2500
Yellowknife (Greenstone Belt)	500
Kirkland Lake	500
Timmins	500
Red Lake	300
Cordova Mine, Cordova, Ontario	5000
Nova Scotia (Meguma Group)	1000
Elliot Lake quartz-pebble conglomerate ores	250
Rand quartz-pebble conglomerate ores	2000

Arsenic, mainly in arsenopyrite, is highly enriched in certain gold-bearing skarn deposits. An excellent example of this type of deposit was the Nickel Plate Mine in British Columbia where the arsenic content was up to 25 per cent and more in the high grade ore. Other gold-bearing skarn deposits have much lower contents of arsenic, usually in the range 100 to 1000 ppm. Most of this is in pyrite, disseminated arsenopyrite and other sulphides and sulphosalts.

Gold-bearing polymetallic deposits are invariably enriched in arsenic as are the typical gold-quartz veins. In these two types of deposits the arsenic content ranges from a few tens of parts per million in the ore to percentage amounts. Some of these deposits are so rich in arsenic minerals that great difficulty is encountered in winning the gold. In fact, in some deposits the gold is so intimately associated with arsenopyrite and arsenic-bearing sulphosalts that the element would appear in many cases to be a lattice constituent of these minerals. This problem is discussed in more detail in a section on gold in other minerals in Chapter II. Arsenic is also commonly found in the alteration zones of both polymetallic deposits and gold-quartz veins in relatively large amounts in some deposits. Our studies show that most of this arsenic is present in disseminated pyrite and/or arsenopyrite. There is frequently a consistent increase in the arsenic content of the wall rocks and alteration zones as the deposits are approached as shown in Tables 44 to 59 inclusive.

The disseminated gold deposits of north-central Nevada, spatially related to the Roberts Mountains thrust fault, including Carlin, Cortez, Getchell and Gold Acres, are all enriched in arsenic (Radtke *et al.*, 1972*a*). The most widely distributed arsenic mineral in the hypogene ores appears to be arsenopyrite, but realgar, as noted above occurs in some abundance in the Getchell and Carlin deposits. The host carbonate rocks 'primary ores' and 'oxidized ores' at Carlin contain respectively in ppm As: <10 to 10; 50 to >10 000; and 40 to >3000. According to the averages given some arsenic is lost during oxidation processes. In the primary ores of the Getchell Mine, Berger (1975) noted a fair statistical relationship between the gold tenor and the arsenic content.

The gold-bearing hot spring precipitates are characterized by high contents of arsenic, some of which is present as orpiment and realgar in certain areas. Weissberg (1969) found up to 2 per cent As in the metal-rich gold-bearing precipitates from hot springs and drillhole discharges in the Taupo volcanic zone of New Zealand. Some of the arsenic is probably present as orpiment. The As/Sb ratio in the precipitates is highly variable ranging from 0.003 to 37.5 in the different springs and drillholes.

The auriferous quartz-pebble conglomerates contain relatively high amounts of arsenic, mainly in the pyrite, according to the writer's investigations. Other arsenic-bearing minerals such as arsenopyrite, cobaltite, gersdorffite and skutterudite appear to be omnipresent in most reefs in the Rand, but their abundance is relatively low judging from the literature on these deposits. Saager and Mihálik (1967) have described two intergrown types of pyrite, forming porous buckshot pyrite in the Rand deposits. The isotropic variety contained 2010 ppm As and the anisotropic variety 8770 ppm As. The respective Ni and Co contents were 1140 and 490 for the isotropic pyrite and 4600 and 2330 for the anisotropic variety. Our analyses show that the arsenic content of the pyrite in the Rand and Elliot Lake conglomerate deposits ranges from 250 to 2000 ppm. In the pyritiferous conglomerate ores as a whole the arsenic appears to range from 28 to 13 600 ppm As (Table 35). The precise relationship of arsenic and gold in these deposits is not known. Correlative studies of the two elements could prove useful in genetic studies of these deposits.

The fate of arsenic during the oxidation of arsenic-bearing deposits has been extensively investigated by the writer and his colleagues (Boyle, 1965*a*, Boyle and Dass, 1971*a*; Boyle, 1972; Boyle and Jonasson, 1973). The details are complex and varied, and only the salient points can be discussed in the space available here.

Arsenic exists in three principal oxidation states in nature, As(0), As(III) and As(V). The first two states are those found in native arsenic, in the sulphide As_2S_3 and in the various arsenides and sulpharsenides. The pentavalent state is the one most stable in an oxidizing environment, being a constituent of a veritable host of arsenates and basic sulphate-arsenates.

Oxidation of native arsenic, arsenopyrite and the various other arsenides and sulpharsenides yields a variety of supergene arsenates and basic arsenate-sulphates the most common being scorodite, $Fe(AsO_4)\cdot 2H_2O$; erythrite, $Co_3(AsO_4)_2\cdot 8H_2O$;

Contents

annabergite $Ni_3(AsO_4)_2 \cdot 8H_2O$; mimetite, $Pb_5(AsO_4)_3Cl$; pharmacosiderite, $Fe_3(AsO_4)_2(OH)_3 \cdot 5H_2O$; adamite, $Zn_2(AsO_4)(OH)$; olivenite, $Cu_2(AsO_4(OH)$; and beudantite, $PbFe_3(AsO_4)(SO_4)(OH)_6$. Of these, the most important in gold deposits is scorodite; the others occur only where there are high contents of Ni, Co, Cu, Pb or Zn. The oxide, As_2O_3 (arsenolite), may form in oxidized zones where water circulation is restricted; being relatively soluble the mineral is not stable in most oxidized zones. The sulphides, orpiment and realgar, and the silver sulphosalt, proustite, may be of supergene origin, but they are relatively rare in the oxidized zones of most gold deposits.

Oxidation of primary arsenic minerals yields soluble arsenic acid, H_3AsO_4, and its derivatives the soluble alkali and alkaline-earth arsenates. In these forms arsenic is relatively mobile, and under certain conditions considerable amounts of the element may be removed from the deposits during oxidation. More generally, however, much of the arsenic, in the form of arsenates, is coprecipitated and/or adsorbed by hydrous iron and other oxides or reacts with cations such as Fe, Cu, Pb, Zn, Co, Ni, etc. to give a variety of insoluble arsenates and basic arsenate-sulphates during various hydrolytic and colloidal reactions in the oxidized zones. These reactions take place mainly between the pH range 4 to 7. In gold deposits the arsenate most commonly formed is scorodite, although in some deposits pharmacosiderite, beudantite and other similar minerals may be present in some abundance. All of these minerals tend to concentrate gold. In Yukon we have found some varieties of scorodite in the oxidized zones of gold deposits to contain as much as 10.3 ppm Au, mostly in the free state. In the gossans of the massive and vein sulphide deposits in the Bathurst area, New Brunswick, scorodite is, likewise, commonly enriched in gold in amounts up to 0.6 ppm. This gold is present in an extremely finely divided form, and some may be in an adsorbed state or in the lattice of the mineral. Beudantite may also be enriched in gold. Samples from the Bathurst gossans contain from 0.4 to 3 ppm Au.

Gold and arsenic exhibit a sympathetic enrichment in the oxidized zones of some gold deposits. In others the oxidized zones are leached of both elements to a considerable degree. In still others gold is markedly enriched and arsenic is strongly leached. The last situation seems to prevail where the wall rocks and gangue contain relatively little carbonate to neutralize the downward moving solutions. Under these conditions the arsenates are not stable, or those that are formed, are gradually dissolved, and the arsenic is carried away in solution. Intense leaching by meteoric waters also leads to the alteration of scorodite to limonite. In such oxidized zones about all that remains is gold-enriched limonite and wad with traces to minor amounts of adsorbed or chemically combined arsenic.

Gold and arsenic may show a sympathic enrichment in some supergene sulphide zones, the gold occurring principally in the free state or in the sulphides and the arsenic being concentrated in secondary pyrite, marcasite and a variety of other sulphides.

Arsenic tends to be enriched in recent and ancient eluvial and alluvial gold placers, especially those containing a relatively high content of limonite particles or limonite-cemented gravels. This is a consequence of the marked adsorptive and coprecipitative capacity of hydrous ferric oxides for arsenate. In some of the limonitic particles and cemented gravels of the Beauceville district, Quebec I have found up to 180 ppm As; in the Carboniferous placers of Gays River, Nova Scotia the limonitic material contains up to 125 ppm As. In the eluvial placers of Dublin Gulch, Yukon the arsenic content in the limonite-clay materials may exceed 400 ppm As. These derive from a terrane containing gold-quartz-arsenopyrite veins. I have also noted arsenopyrite and arsenic-bearing pyrite in nearly all of the heavy mineral concentrates of the gold placers in Yukon and elsewhere in Canada.

Antimony exhibits a nearly universal enrichment in most types of hypogene gold deposits, and there is a marked coherence between gold and antimony during both hypogene and supergene processes. This relationship also extends to the plant kingdom (*see* the section on Biogeochemistry). Gold forms a mineral with antimony, aurostibite, $AuSb_2$. This mineral is generally hypogene in origin, usually formed late in the paragenetic sequence and probably at relatively low temperatures.

The common antimony minerals in hypogene gold deposits are stibnite, tetrahedrite-tennantite and a variety of other sulphosalts of which the most persistent are jamesonite, boulangerite, bournonite, meneghinite, jordanite, chalcostibite, zinkenite, berthierite and semseyite. Native antimony is not particulary common in gold deposits, although it has been found in small amounts in the Engineer Gold Mine, Yukon (allemontite), in the antimony-rich Yellowknife ores, at West Gore, Nova Scotia and elsewhere. The silver sulphosalts, pyrargyrite, polybasite and stephanite are relatively uncommon minerals in most gold deposits, although in some gold-bearing polymetallic deposits and in some of the great (mainly Tertiary) Au-Ag bonanzas of the world these minerals may be relatively abundant. When antimony minerals are absent in gold deposits, the element is largely camouflaged in pyrite, marcasite or arsenopyrite. Some average antimony values for pyrite and arsenopyrite, where antimony minerals are rare or absent in the gold ore shoots of deposits, are given below:

Location and mineral	Sb (ppm)
Keno Hill (pyrite)	100
Keno Hill (arsenopyrite)	500
Yellowknife Greenstone Belt (pyrite)	100
Yellowknife Greenstone Belt (arsenopyrite)	400
Kirkland Lake (pyrite)	8
Timmins (pyrite)	20
Red Lake (pyrite)	10
Cordova Mine, Cordova, Ontario (pyrite)	20
Nova Scotia (Meguma Group; pyrite, arsenopyrite)	2–100
Elliot Lake quartz-pebble conglomerate ores (pyrite)	2
Rand quartz-pebble conglomerate ores (pyrite)	4

Antimony is not particularly enriched in gold-bearing skarn deposits in contrast to arsenic. Antimony minerals are relatively rare in skarn deposits, although tetrahedrite has been noted in small amounts in a number of these deposits (e.g., New Calumet Mine, Quebec). Where pyrite and arsenopyrite are abundant in the ores the antimony content may be relatively high, up to 50 ppm Sb or more.

Gold-bearing polymetallic deposits are invariably enriched in antimony, as are some of the typical gold-quartz veins. In these two types of deposits the antimony ranges from a few tens of parts per million in the ore to percentage amounts. Some of the gold-quartz deposits are so rich in antimony minerals, mainly stibnite and sulphosalts, that great difficulty is encountered in winning the gold. It is in these deposits that the gold antimonide, aurostibite, frequently makes its appearance. Gold also appears to substitute in the lattice of a number of the antimony sulphosalts in these deposits, principally in tetrahedrite-tennantite. Antimony is also commonly found in the alteration zones of both polymetallic deposits and gold-quartz veins, in relatively large amounts in some deposits. Our studies show that most of this antimony is present in disseminated pyrite and/or arsenopyrite. There is frequently a consistent increase in the antimony content of the wall rocks and alteration zones as the deposits are approached as shown in Tables 44 to 59 inclusive.

The disseminated gold deposits of north-central Nevada, including Carlin, Cortez, Getchell and Gold Acres, are all enriched in antimony (Radtke *et al.*, 1972*a*). The antimony mineral in these deposits is mainly stibnite and antimoniferous orpiment. The host carbonate rocks, 'primary ores', and 'oxidized ores' at Carlin contain respectively in ppm Sb: <0.5 to 3; 5 to 450; and 5 to 450. According to the averages given there is relatively little change in antimony content during oxidation processes. Berger (1975) found no significant statistical relationship between the gold and antimony contents in the primary ores of the Getchell Mine.

The gold-bearing hot-spring precipitates are characterized by high contents of antimony, some of which is present as stibnite in certain areas. Weissberg (1969) found up to 30 per cent Sb in the metal-rich gold-bearing precipitates from hot springs and drillhole discharges in the Taupo volcanic zone of New Zealand. Some of the antimony is probably present as stibnite. The As/Sb ratio in the precipitates is highly variable ranging from 0.003 to 37.5 in the different springs and drillholes.

The auriferous quartz-pebble conglomerate deposits contain some antimony mainly in the pyrite according to our investigations. Other antimony-bearing minerals are relatively rare in these deposits; Saager (1968) recorded the presence of tennantite, proustite and dyscrasite in the Basal Reef in the Free State Geduld Mine, near Welkom in the Orange Free State Goldfield; Feather and Koen (1975) record the presence of stibnite locally in some of the Rand reefs. Galena is relatively common in some of the auriferous conglomerates of the Rand, and it may contain some antimony. There may also be more silver-antimony sulphosalts in the ores than is generally thought judging from the research by Saager (1969) on the gold-silver relationships. Geological Survey analyses show that the antimony content of the pyrite in the Rand and Elliot Lake conglomerates ranges from 2 to 4 ppm. In the pyritiferous conglomerate ores of the Rand as a whole the antimony content appears to average about 3 ppm (Table 35). The relationship of antimony and gold in the conglomerates is not known. Correlative studies of the two elements could prove useful in genetic studies of these deposits.

The fate of antimony during the oxidation of antimony-bearing deposits has been extensively studied by the writer and his colleagues (Boyle, 1965*a*; Boyle and Dass, 1971*a*; Boyle, 1972). The details are particularly complex and only the salient points can be discussed in the space available here.

Antimony exists in three principal oxidation states in nature: Sb(0), Sb(III) and Sb(V). The first two states are those found in native antimony, in the sulphide, Sb_2S_3, and in the various antimonides and sulphantimonides. The pentavalent state is the most stable in an oxidizing environment, being a constituent of a number of the natural oxides (cervantite, stibiconite) and antimonates.

Oxidation of native antimony, stibnite and the various other antimonides and sulphantimonides yields a variety of supergene antimony minerals the most common being cervantite, $Sb_2O_3 \cdot Sb_2O_5$, senarmontite, Sb_2O_3, valentinite, Sb_2O_3, stibiconite, $Sb(III)Sb(V)_2(O,OH,H_2O)_7$, kermesite, Sb_2S_2O, bindheimite, $Pb_{2-y}Sb_{2-x}(O,OH,H_2O)_{6-7}$, romeite, $(Ca,Na)_{2}$-$Sb_2(O,OH)_7$, and numerous other antimonites and antimonates. Yellow and white ocherous antimony compounds that are amorphous to X-rays characterize the oxidation zones of many gold deposits containing abundant hypogene antimony minerals.

Oxidation of primary antimony minerals yields the various oxides which are only sparingly soluble in solutions with pH ranging from 4 to 8 and hence these minerals have a relatively high degree of stability in most oxidized zones. The trivalent oxide is amphoteric yielding $[Sb(OH)_2]^+$ ions in acid solutions and antimonite anions usually written as $[Sb(OH)_4]^-$ in basic solutions. The cationic complex is particularly prone to hydrolysis on dilution or neutralization of acidic solutions and the hydrous trioxide is precipitated. Antimonites, precipitated as a result of the reaction of various cations such as Ca and Fe with antimonite-bearing solutions, are relatively rare. The pentavalent oxide is acidic dissolving in base to give antimonate anion, usually written as $[Sb(OH)_6]^-$. Reactions of this complex and/or the various derivatives of antimonic acid with cations, particularly lead and iron, yield a number of insoluble minerals of which bindheimite and tripuhyite are the most common.

Under very acid ($pH<3$) and highly alkaline ($pH>8$) conditions much antimony is removed from deposits during oxidation processes. Under more normal pH conditions (4–8) much of the antimony is retained in the oxidized zones in the form of oxides and various antimonites and antimonates and in an adsorbed or chemically combined state in limonite and wad. There may also be considerable amounts of antimony camouflaged in the various arsenates and a variety of other supergene minerals. In the Keno Hill deposits a depletion of antimony and gold was noted in the oxidized zones of some deposits and a sympathetic enrichment of both elements in others compared with the primary ores (Boyle, 1965). At Yellowknife the writer observed a general enrichment of both elements in the shallow oxidized zones of some veins. In some of the gossans overlying the massive sulphide deposits of the Bathurst district, New Brunswick both gold and antimony are considerably enriched. Under conditions of intense leaching by groundwaters antimony is largely removed from the gossans and oxidized zones. This effect is particularly marked where the wall rocks and gangue contain relatively little carbonate to neutralize the downward moving acidic solutions. In such oxidized zones about all that remains is gold-enriched limonite and wad with traces to minor amounts of adsorbed or chemically combined antimony.

Gold and antimony may show a sympathetic enrichment in some supergene sulphide zones, the gold occurring principally in the free state or in the sulphides and the antimony being concentrated in secondary pyrite, marcasite and a variety of other sulphides. Aurostibite in some of the near surface parts of the Yellowknife veins may be of supergene origin, although this is difficult to verify.

Antimony tends to be enriched in recent and ancient eluvial and alluvial gold placers, especially those containing a relatively high content of limonite particles or limonite-cemented gravels. This is a consequence of the marked adsorptive and coprecipitative capacity of hydrous ferric and manganese oxides for antimonate. In some of the limonite particles and cemented conglomerates of the Carboniferous placer of Gays River, Nova Scotia I have found from 2 to 12 ppm Sb. In the limonite-cemented conglomerate of the Beauceville district, Quebec, on the other hand, only <2 ppm Sb was obtained. These differences evidently reflect the provenance of the element in the parent terrane of the placer deposits. In the case of Gays River, antimony and arsenic are relatively abundant in the Meguma Group whereas these elements are relatively rare in the rocks and deposits of the Beauceville district. In the eluvial placers of Dublin Gulch, Yukon the antimony content of the limonite-clay materials may exceed 10 ppm. These derive from a terrane containing gold-quartz-arsenopyrite-jamesonite veins. I have also noted jamesonite, boulangerite and antimony-bearing pyrite in many of the heavy mineral concentrates of the gold placers in Yukon and elsewhere in Canada.

Bismuth is a common associate of gold in some hypogene deposits, although it is generally present in only small amounts (<5 ppm) in most gold ores. There is a coherence between gold and bismuth exemplified by the fact that gold bismuthide (maldonite, Au_2Bi) occurs in nature.

The common bismuth minerals in hypogene gold deposits are bismuthinite, native bismuth, galenobismutite, bismuthian tetrahedrite-tennantite (goldfieldite), wittichenite and various bismuth tellurides and selenides including joseite, hedleyite, tellurbismuth, wehrlite and guanajuatite. Tetradymite, cosalite and other bismuth minerals are relatively rare in gold deposits. When bismuth minerals are absent in gold deposits, the element may be present in small amounts in a great variety of sulphides and sulphosalts. At Yellowknife the writer has noted the presence of bismuth in samples of arsenopyrite (~10 ppm), pyrite (<10 ppm), stibnite (~10 ppm), various sulphosalts, particularly tetrahedrite (~100 ppm), sphalerite (<10 ppm), chalcopyrite (~10 ppm) and galena (~100 ppm). In the Keno Hill area some of the galena in the gold-quartz veins is rich in bismuth (up to 8000 ppm) as are also jamesonite and boulangerite (up to 500 ppm).

Bismuth may be slightly enriched in gold-bearing skarn zones, the principal bismuth minerals being native bismuth, bismuthinite and bismuth tellurides. The tellurides frequently exhibit a close relationship with native gold as in the French Mine, Hedley district, British Columbia. Most of the ores in the gold-bearing skarn category rarely contain more than 10 ppm Bi.

Some gold-bearing polymetallic deposits and typical gold-quartz veins may be enriched in bismuth. Typical examples occur in Queensland (Burnett district), Northern Territory (Tennant Creek) and New South Wales, Australia; Norway (Svartdal); Japan (Nishizawa and Nakanosawa mines); the United States (Goldfield); U.S.S.R. (Darasun and Sredniy Golgotay goldfields); Canada (Hazelton and other areas in British Columbia); France (Salsigne-Aude) and elsewhere. In the Tennant Creek Juno deposit the most abundant bismuth-bearing mineral is junoite, $Bi_8Pb_3Cu_2(S,Se)_{16}$, a new mineral described by Large and Mumme (1975) and Mumme (1975). It is accompanied by the bismuth-selenium sulphosalt, wittite and a variety of other selenium-bearing sulphosalts. One of the best known examples of the gold-silver-bismuth type of deposits is at Goldfield, Nevada, where bismuthinite is found with pyrite, marcasite, sphalerite, enargite, tellurium-bismuth tetrahedrite (goldfieldite), arsenical famatinite, tennantite, various gold-silver tellurides and native gold, all in irregular silicified and alunitized zones referred to as "ledges" by Ransome (1909). Lindgren (1933) gives an analysis of rich ore from the Mohawk Mine which indicates 0.35 per cent Bi (3500 ppm). This is a high assay; most gold-bismuth deposits contain bismuth in the range 10–100 ppm in the ore. At Kirkland Lake for instance the ores of the Upper Canada Mine contain from 5 to 11 ppm Bi.

There are no data on the bismuth content in the disseminated gold deposits of north-central Nevada (e.g., Carlin, Cortez). Likewise, data are particularly sparse on the bismuth content of gold-bearing precipitates associated with present day hot springs. Browne (1969) records the presence of bismuth (0.003 ppm) and gold (0.0001–0.001 ppm) in the water of the Broadlands Geothermal drillhole, Taupo volcano zone, New Zealand. Base metal sulphides have been deposited in rocks penetrated by this drillhole, and enriched gold-bearing precipitates are associated with the hot springs and steam wells in the area (*see also* under arsenic and antimony).

There are no published data on the bismuth content of the gold-bearing conglomerate ores, nor, excepting the rare occurrence of michenerite, (Pd,Pt)BiTe, in the Rand, are there any references to the presence of bismuth minerals in these ores. Our analyses (Table 35) show that the bismuth content of the Rand ores runs from not found to 2.2 ppm; in the Elliot Lake ores the content averages about 43 ppm Bi. The pyrite in the Elliot Lake ores is also rich in bismuth (40 ppm). Some of the bismuth in these ores may be of radiogenic origin.

The fate of bismuth during the oxidation of bismuth-bearing deposits has been investigated by the writer and his colleagues (Boyle, 1965*a*; Boyle and Dass, 1971*a*). Only a few of the salient points can be discussed here.

The principal supergene bismuth minerals in gold deposits are bismite-sillenite Bi_2O_3, bismutite, $(BiO)_2CO_3$, bismoclite-daubreeite, BiO(OH,Cl) and montanite, $Bi_2TeO_6{\cdot}2H_2O$. There are also supergene bismuth arsenates, vanadates, molybdates and complex uranates, but these are relatively rare in gold deposits. Bismuth ochres, which are probably mixtures of the oxide and carbonate but are amorphous to X-rays, are common in some oxidized zones.

Bismuth exists in two oxidation states in nature, Bi(0) and Bi(III). The pentavalent state, Bi(V), is apparently not reached under the oxidation potentials existing in nature, since no mineral 'bismuthates' are known. The first two states are those found in native bismuth, in the sulphide, Bi_2S_3, in the oxide Bi_2O_3 and in the various bismuthides and complex bismuth sulphosalts. The oxide, Bi_2O_3, is basic and is practically insoluble in water. It does dissolve however, in acidic solutions yielding hydrolized bismuth (bismuthyl) ion that can be characterized as $[BiO]^+$, $[BiOH]^{2+}$ or $[Bi(OH)_2]^+$. It is probably in this form that the small amounts of bismuth migrate in the oxidized waters of gold deposits.

Studies by the writer indicate that native bismuth oxidizes slowly in oxygenated water, forming a hydrous oxide from which water is split out to give the yellow oxide, Bi_2O_3, bismite. Bismuthinite, Bi_2S_3, bismuthian tetrahedrite, bismuth tellurides and the various other primary bismuth minerals also yield the oxide directly, or hydrolyzed bismuth ion, which follows a number of courses depending on the pH and the presence of other constituents. If the pH is low some bismuth is leached from the deposits. On neutralization of the solutions the bismuth ion undergoes rapid hydrolysis with the precipitation of the oxide or hydroxide. If CO_2 is present in the solutions bismuthyl carbonate (bismutite) may form in two ways, one by direct precipitation and the other by reaction of CO_2 with the hydroxide. The two reactions can be expressed as follows:

$$4(BiO)^+ + O_2 + 2CO_2 = 2(BiO)_2CO_3 \text{ (bismutite)}$$

$$2Bi(OH)_3 + CO_2 = (BiO)_2CO_3 \text{ (bismutite)} + 3H_2O$$

Bismutite may also be found where carbonates are present in the gangue or wall rocks. The simple reactions in this case involve the formation of hydrogen carbonate ion, which fixes the bismuthyl ion as the carbonate:

$$CaCO_3 + CO_2 + H_2O = Ca^{2+} + 2(HCO_3)^-$$

$$2(BiO)^+ + (HCO_3)^- = (BiO)_2CO_3 \text{ (bismutite)} + H^+$$

Bismite and bismutite are the most common supergene bismuth minerals, but where other constituents are present in the oxidizing solutions a variety of secondary bismuth minerals may be formed in the pH range 4 to 8. Arsenate precipitates bismuthyl ion as insoluble arsenates; tellurate as montanite; chloride as bismoclite or daubreeite; vandate as pucherite, $BiVO_4$; and so on. In addition bismuthyl ion is adsorbed and/or coprecipitated probably as the oxide or hydroxide by hydrous ferric oxides (limonite), hydrous manganese oxides (wad) and hydrous silica-alumina complexes. Much bismuth is also adsorbed and/or absorbed in some manner or other by minerals such as senarmontite, bindheimite, anglesite and jarosite. In these secondary minerals I have found bismuth contents ranging from 100 to 1000 ppm. As noted previously some of these minerals also tend to concentrate gold.

From the above discussion it will be seen that bismuth is enriched in oxidation zones where the pH of the waters lies in the range 4 to 8, that is, where carbonate gangue of wall rocks is available to neutralize the acid waters generated during the oxidation of sulphides such as pyrite. Under these conditions gold is also enriched in the gossans and underlying oxidized parts of the deposits. In some highly oxidized deposits native bismuth encrusted with bismite and/or bismutite and large particles of gold may be present in the rubble. These are largely residuals. Where the oxidizing waters retain their acidity some bismuth is leached, and hence gold and bismuth tend to part company since gold tends to remain behind in the gossans and oxidized zones under such conditions. The amount of bismuth passing downward in oxidizing waters in most deposits is relatively low, generally in the range 0.0001 to 0.001 ppm where bismuth minerals are present in the ores. Some of this bismuth may be precipitated together with gold in the secondary sulphide zones of deposits (Naumov *et al.,* 1971).

There are few data on the presence of bismuth in recent and ancient gold placers. Native bismuth and bismuthinite are relatively resistant to oxidation when coated with bismite and bismutite. In this condition the element is a persistent constituent of the gold placers of the Dublin Gulch area, Yukon. Tetradymite has also been found in these placers. There are scattered references in the literature noting the occurrence of native bismuth, bismuthinite and bismuth tellurides in gold placers in many parts of the world. Various other bismuth-bearing minerals have also been found in small amounts in the heavy concentrates of gold placers, including galena, various sulphosalts, bismutotantalite and bismuthian gold.

Group VB: V, Nb, Ta

Vanadium is present in some hypogene gold deposits principally in minerals like sericite, roscoelite, pyrite, apatite, magnetite, ilmenite and leucoxene. At Yellowknife the element was found in amounts up to 100 ppm in all of these minerals in the wall-rock alteration zones and in the gold ores. Most of the vanadium appears to have been contributed by the host rocks (meta-andesites). There is no correlation of vanadium with gold in the Yellowknife deposits nor in any other auriferous vein deposits investigated by the writer. For other vein deposits there may be a correlation between the two elements as noted below.

Vanadium is present in the gold-bearing conglomerates of the Rand in amounts ranging from 15 to 96 ppm (Table 35), apparently mainly in the pyrite and micas (sericite). There appears to be no particular correlation between gold and vanadium in these ores as far as the writer is able to ascertain.

Roscoelite, $K(V,Al)_3(AlSi_3)O_{10}(OH)_2$, is reported to occur in some abundance in a few of the gold veins of the Mother Lode system northwest of Placerville, El Dorado County, California; also at Cripple Creek, Colorado, and at Kalgoorlie, Western Australia. According to Lindgren (1933) the roscoelite in the Mother Lode system often accompanies native gold. At Cripple Creek, according to the same authority, roscoelite is often abundant in rich ore. In the Kalgoorlie gold belt vanadium mica is apparently common in rich shoots of gold and gold tellurides according to some authors. It should be mentioned that gold ores rich in tellurides frequently seem to have higher than average amounts of vanadium either in pyrite or in the vanadiferous micas. The reason for the relationship between the three elements, Te, V and Au, is obscure to the writer, but should be borne in mind by those carrying out further investigations on these ores. Perhaps the relationship is connected with the fact that gold and gold tellurides commonly occur in host rocks that are relatively rich in vanadium (e.g., basic to intermediate volcanics, serpentinites, etc.)

Vanadium minerals may be present in gold ores containing uranium and rare earth minerals. The Nicholson deposits in the Goldfields area, Saskatchewan, contains nolanite, $Fe_3V_7O_{16}$, in some abundance (Robinson, 1955). The relationship of the gold values to this mineral is unknown.

Nolanite has also been observed in nonuraniferous ores, particularly in the South Kalgoorlie Mine along the Golden Mile at Kalgoorlie, Australia (Taylor and Radtke, 1967). There, the mineral is closely associated with native gold and numerous Au-Ag tellurides. In the paragenetic sequence coloradoite and native gold are younger than the nolanite. In further research on the 'green leader' at Kalgoorlie, Nickel (1977) recognized sericitic vanadium muscovite, nolanite and an unidentified titanium vanadate. The color of the 'green leader' is due to vanadium muscovite in which the vanadium is present in the trivalent state.

In the disseminated gold ores of Carlin, Nevada, Radtke *et al.* (1972*a*) report the following vanadium contents for host carbonate rocks, 'primary ores', and 'oxidized ores' respectively: 10 to 500, 15 to 500 and 50 to 1500 ppm. The oxidized ores are apparently not enriched according to the averages given for the 'primary ores' (140 ppm V) and 'oxidized ores' (140 ppm V).

Concentrations of *niobium* and *tantalum* have not been detected in any of the hypogene gold deposits examined by the writer. This was expected since deposits containing Nb and Ta are commonly found in quite different environments than those characterized by the presence of gold, a feature also remarked upon by Sadovskii *et al.* (1971). The contents of niobium in the skarn, gold-quartz and polymetallic ores investigated were all less than 5 ppm; similarly the tantalum contents never exceeded 2 ppm. In the quartz-pebble conglomerate ores the niobium contents range from 4 to 18 ppm with the highest amounts in the Rand ores; the tantalum contents were <3 ppm in all occurrences (Table 35). In the Carlin, Nevada disseminated ores Radtke *et al.* (1972*a*) recorded the following ranges in the host carbonate rocks, 'primary ores' and 'oxidized ores' respectively: <7 to 7; <7 to 15; and <7 to 20 ppm Nb. Tantalum was not found.

The heavy resistate minerals of vanadium, niobium and tantalum frequently accompany gold in recent and fossil placers. The most common vanadium-bearing minerals in these surficial deposits are magnetite, ilmenite, rutile and apatite, which are usually present in some abundance. Tantalite-columbite, pyrochlore, fergusonite, euxenite and a variety of other niobates and tantalates may occur in gold placers, but they are usually rare or present in only small amounts. There appears to be no particular correlation between gold and the vanadium-, niobium- and tantalum-bearing resistates in placers, a circumstance to be expected since these minerals are largely contributed by the host rocks and deposits such as pegmatites that are either devoid of gold or are unrelated genetically to gold deposits.

Group VIA: O, S, Se, Te

Oxygen does not combine with gold in nature, and there are no known natural gold oxides. Numerous other oxygen compounds occur with gold in all of its deposits. These are discussed above and below.

Sulphur is a constant associate of gold in all types of deposits, being present mainly in pyrite, arsenopyrite, chalcopyrite, sphalerite, galena and numerous other sulphides and sulphosalts. Hypogene sulphates are relatively uncommon gangue minerals in most hypogene gold deposits, but some deposits are notably enriched in some of these minerals. Barite is a gangue mineral in a number of gold deposits, principally the polymetallic and gold-quartz type. Anhydrite and gypsum are much more common in gold deposits than is generally realized, being present in both the polymetallic and gold-quartz type of all ages, often in some abundance. Alunite, the basic hydrous potassium aluminum sulphate, is a characteristic mineral in the gold-quartz-alunite assemblage exemplified by Goldfield, Nevada and other deposits.

Gold and its various minerals exhibit a very close association with a number of sulphides, sulphide-arsenides and sulphosalts. Of these the most common associates of gold are pyrite and arsenopyrite. In some cases it is evident that the element is a lattice constituent of these minerals as discussed in Chapter II; in other cases the gold is of later generation and may have exsolved from these two minerals. The other sulphur minerals with which gold and its minerals show an intimate association are chalcopyrite, galena, sphalerite, tetrahedrite-tennantite and stibnite. Their relationship with gold is discussed further in the section on mineral associates of gold.

The most common sulphide in the auriferous quartz-pebble conglomerate deposits is pyrite. Other sulphur-bearing minerals present in trace and minor amounts in the Rand ores include the following: arsenopyrite, stibnite, marcasite, glaucodot, pyrrhotite, sphalerite, galena, chalcopyrite, cubanite, bornite, chalcocite, covellite, chalcopyrrhotite, bravoite, molybdenite, mackinawite, niccolite, millerite, pentlandite, cobaltite, linnaeite, gersdorffite, skutterudite, safflorite, tetrahedrite-tennantite, stromeyerite and proustite (Saager, 1968; Feather and Koen, 1975). Not all the quartz-pebble conglomerate deposits are enriched in sulphur-bearing minerals. The Tarkwa conglomerate ores in Ghana carry mainly hematite; pyrite and other sulphides are very rare.

During oxidation processes the sulphides, sulphide-arsenides and sulphosalts generally yield either normal sulphates, acid sulphates or basic sulphates depending on the pH, Eh and various complicated hydrolytic phenomena. Thiosulphate, sulphite and a variety of other polymerized oxidized sulphur species may form as intermediate products during the oxidation of sulphides and sulphosalts as noted in Chapters II and IV. These species are, however, probably only transitory, being oxidized on to sulphate in most natural environments. Most of these species are also only stable under alkaline conditions. When present some are good solvents of gold and silver as mentioned in Chapter II. Relatively large amounts of gold may, therefore, be transported in oxidized zones where species such as thiosulphate are formed. As noted in Chapter II, gold is not readily soluble as the sulphate, and it seems probable that relatively little of the metal migrates as a simple sulphate. Some may migrate as complex sulphates, but little is known about these species.

Most sulphates are soluble (>1 g/100 mL) except those of Sr, Ba, Ra and Pb (<0.1 g/100 mL). The sulphates of Ca,

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Ag and Hg are sparingly soluble. The oxidation and leaching of gold deposits containing sulphides results in most cases in a strong depletion in the amount of sulphur in the oxidized zones. This depletion varies from place to place but is rarely less than 25 per cent in most oxidized zones and may exceed 95 per cent in some. The sulphur, which is set free as sulphate or oxidized polymerized species in the oxidized zones of gold deposits containing sulphides, may follow three main courses. Some is precipitated as insoluble sulphates, mainly anglesite and gypsum, or as basic sulphates or basic sulphate-arsenates such as jarosite and beudantite. Gold is frequently concentrated in these minerals, particularly in the basic sulphate-arsenates. In some jarosites for instance gold (mainly in the native form) may occur in amounts up to 7900 ppm; in minerals like beudantite we have found up to 0.7 ppm Au. Under certain conditions a considerable portion of the oxidized sulphur species is reduced and precipitated as various sulphides in the zones of reduction (secondary sulphide zones). Gold may be enriched in these zones. The remaider of the sulphur, mainly as sulphate, passes into the groundwater system and ultimately through springs into the stream systems of the area.

The fate of gold and sulphur during oxidation processes can be summarized as follows: in the highly oxidized and leached zones sulphur and gold tend to part company; much of the gold remains behind in the gossans and the sulphur (mainly as sulphate) is leached. Where basic sulphates and basic arsenate-sulphates are formed during the neutralization of acid sulphate solutions some gold may be concentrated in these minerals. Gold and sulphur passing downward are both precipitated in the secondary sulphide zones of the deposits where the appropriate conditions for reduction of sulphate and soluble gold compounds are present. Under certain conditions native sulphur may form in the oxidized zones of auriferous deposits, evidently as the result of the oxidation of H_2S. When this occurs finely divided gold, wires and mossy aggregates of the metal are commonly concentrated in the sulphur.

Sulphur accompanies gold in recent and ancient eluvial and alluvial placers, being present mainly in pyrite, arsenopyrite, galena and a variety of other sulphides and sulphosalts. The total quantity of these minerals is never great, rarely more than a few per cent of the heavy mineral suite. Pyrite is by far the most abundant of the sulphides, etc. in placers. Barite is present in a few gold placers, often in some abundance, but its distribution is generally local. Anglesite may occur in some gold placers near veins containing lead minerals. Gypsum crystals are common in the clays and weathered residuum of eluvial placers but are relatively uncommon in alluvial placers.

Selenium follows sulphur closely in nature and is hence a nearly universal associate of gold in its deposits. In some gold-bearing deposits selenium exhibits a marked enrichment; in others only traces of the element are present. Gold selenide *sensu strictu* has not yet been verified in nature, although there are a number of reports suggesting its occurrence, especially in the selenium-rich gold deposits. A silver-gold selenide, fischesserite, Ag_3AuSe_2, has recently been described.

Practically all sulphides, sulphosalts, sulphates and other species of sulphur minerals contain selenium, but the amounts are highly variable. The element is frequently enriched in minerals such as pyrite, chalcopyrite, bismuthinite, tetrahedrite and some of the other sulphosalts, various sulphates, etc. in which selenium replaces or substitutes for sulphur. Selenium combines readily with Cu, Ag, Pb, Bi and Hg forming a number of individual hypogene minerals of which the most common are umangite, Cu_3Se_2, klockmannite, CuSe, penroseite, $(Ni,Cu)Se_2$, naumannite, Ag_2Se, aguilarite, Ag_4SeS, clausthalite, PbSe, tiemannite, HgSe, guanajuatite, $Bi_2(Se,S)_3$, and junoite, $Bi_8Pb_3Cu_2(S,Se)_{16}$. Supergene species include the oxide, selenolite, SeO_2, and a number of selenites and selenates, viz. chalcomenite, $CuSeO_3{\cdot}2H_2O$, ahfeldite, $NiSeO_3{\cdot}2H_2O$, kerstenite, $PbSeO_4{\cdot}2H_2O$, selenojarosite, and others. All of these are relatively rare minerals.

A number of gold deposits are greatly enriched in selenium. Most of these occur within relatively restricted metallogenic zones that seem to be characterized by the presence of the selenides. Examples occur in the Tonapah area of Nevada; the De Lamar area of Idaho; in the Republic Mine, Republic, Washington; in the Radjang-Lebong goldfield, Sumatra, Indonesia; in the Waihi, Maratoto, Tui and Great Barrier Island lodes of New Zealand; and in the Goldfields area of Saskatchewan. Selenium (0.05%) is present in the auriferous magnetite ores of the Juno Mine in the Tennant Creek Goldfield, Northern Territory, Australia. Certain auriferous uranium-bearing deposits may be enriched in selenium (e.g., Nicholson Mines, Goldfields, Saskatchewan). At Tennant Creek the element occurs in a variety of selenium-bearing sulphosalts including wittite, heyrovskyite and the new mineral junoite, $Bi_8Pb_3Cu_2(S,Se)_{16}$ (Large and Mumme, 1975). In additon to the presence of selenides in auriferous deposits it is commonly noted that the other sulphides and sulphosalts are greatly enriched in selenium, particularly galena, tetrahedrite, tennanite, polybasite, argyrodite and so on. It is of interest to note that these selenium-rich deposits contain few if any tellurides; in fact tellurides and selenides are rather rare companions in most gold deposits.

Excepting the selenium-rich gold deposits, some of which contain up to 200 ppm Se in the ores, most gold-quartz and skarn-type deposits contain relatively little selenium, usually in the range from 1 to 10 ppm in the ores. With increase in sulphides in these deposits there is generally an increase in the selenium content. Polymetallic-type gold deposits usually report relatively high selenium contents, in the range from 10 to 400 ppm or more. The quartz-pebble conglomerates of the Rand contain from 1 to 2 ppm Se (Table 35). The element is mainly in pyrite. In the disseminated gold ores of Carlin, Nevada, Radtke *et al.* (1972*a*) found <1 to 20 ppm Se in the 'primary ores' and <1 to 40 ppm in the 'oxidized ores'. There is no apparent correlation between selenium and gold values in auriferous deposits according to our analytical data.

Berzon and Karyshev (1973) have investigated the Te/Se ratio in the gold deposits of the Urals and have grouped the deposits according to the value of this ratio. (*See* the discussion in the following section on tellurium.)

Selenium occurs in nature in the minus(II), (0), (IV) and (VI) oxidation states. Of these, the (IV) and (VI) states are of interest during oxidation processes. The (IV) state is that contained in the oxide, SeO_2, and various selenites, and the (VI) state prevails in the selenate ion, $[SeO_4]^{2-}$. Chemically, selenium is like sulphur in most respects and similar to arsenic in a few features. A review of the geochemistry of selenium is given by Vlasov (1966–1968).

The oxidation of seleniferous pyrite, selenides and other hypogene selenium-bearing minerals in gold deposits is complex and not particularly well understood. Only a general outline is given here since our research on selenium is not yet complete. Under conditions of low Eh, oxidation of selenium minerals yields selenious acid (H_2SeO_3) and selenite ions to the meteoric waters, and these may migrate considerable distances. Native selenium (and seleniferous sulphur or sulphurous selenium) may also be formed in some oxidized zones by a variety of mechanisms, but these minerals are generally rare. Selenolite, SeO_2, may form in dry places, but this mineral is also rare because of its high solubility. Selenite ions and selenious acid tend to be adsorbed by a variety of colloidal substances, especially hydrous iron oxides with which they form very insoluble basic ferric selenite in the pH range 3.5–9. Various cations, principally Ca, Na, K, Cu, Pb, Ni, Co and Fe, and hydrolytic products of these ions, may combine with selenite ion to form a number of insoluble products, poorly differentiated as minerals. Under conditions of higher oxidation potential selenium is oxidized to the VI state and migrates as selenic acid (H_2SeO_4) or various soluble selenates. Selenates and selenic acid are also strongly adsorbed and/or coprecipitated by hydrous iron oxides in the pH range 5 to 7. Selenate ion is also readily incorporated in various normal sulphates and in basic sulphates such as jarosite. Numerous cations and their hydrolytic products, particularly Fe, Pb, Ni and Co, precipitate insoluble compounds, poorly differentiated as minerals. Where soluble selenium species pass into the zone of reduction of gold-bearing sulphide deposits, some of the element as selenide is incorporated in supergene sulphides such as pyrite, marcasite, covellite and chalcocite.

Comparing the migration tendencies of sulphur and selenium it is evident from a consideration of the appropriate oxidation potentials that the latter element is much less mobile in some environments than the former. This is because selenium requires a higher oxidation potential to mobilize it as soluble species, and these when formed are much more easily reduced than the soluble sulphur species. It would also appear from our studies that selenium in its various soluble states is much more susceptible to adsorption by hydrous ferric oxides and other similar colloidal substances. Because of these features sulphur and selenium may be separated in some oxidized zones, the sulphur being largely removed whereas considerable amounts of selenium remain behind.

In some oxidized zones gold and selenium may exhibit a sympathetic enrichment, especially where secondary sulphates and basic sulphates such as jarosite are present. In others, the two elements part company, the selenium being largely removed whereas much of the gold remains behind in the gossans. This condition prevails particularly where the waters have an acid reaction or where large volumes of water, with either an acid or alkaline reaction, pass through the oxidized zones. In the zones of reduction (secondary sulphide zones) gold and selenium may again exhibit a sympathetic enrichment.

Generally speaking selenium tends to be concentrated in the gossans and weathered rubble of gold-bearing deposits in Canada. For example, at Yellowknife and Sudbury the enrichments shown in Table 39 in the gossans compared with the primary ores have been noted.

There are no data on the occurrence of selenium in fossil and recent eluvial and alluvial placers. Presumably traces of the element are present in the sulphides and other sulphur minerals that frequently accompany gold in these deposits.

Table 39. Selenium, tellurium and gold contents of primary ores and gossans of some Canadian gold-bearing deposits

Location	Se in ore	Se in gossan	Te in ore	Te in gossan	Au in ore	Au in gossan
			(ppm)			
Lynx deposit, Yellowknife, N.W.T. (gold-quartz type)	1	33	<0.2	4.0	0.034	0.17
Vermilion deposit, Sudbury, Ont. (polymetallic type)	165	250	115	160	1.9	0.54

Tellurium appears to be a nearly constant associate of gold in all types of deposits, according to the writer's investigations. The element is particularly abundant in some types of gold-quartz deposits, e.g., Kirkland Lake, Ontario; Kalgoorlie, Australia; Nagyág, Romania; and Cripple Creek, Colorado. All of these deposits are in or near volcanic rocks of widely differing ages. Tellurium is present in most gold-bearing skarn deposits but generally only in small amounts. Auriferous polymetallic deposits invariably contain some tellurium, and certain auriferous uranium-bearing deposits may be slightly enriched in the element (e.g., Jabiluka deposit, Northern Teritory, Australia). The conglomerate type of gold deposit seems to be relatively low in the element, but my data are not extensive for these deposits (Table 35). The only tellurides in the Rand ores are michenerite; (Pd,Pt)BiTe, and moncheite, $PtTe_2$ (Feather and Koen, 1975).

Analyses by the Geological Survey laboratories of gold-ores show the following general ranges for tellurium, in ppm:

Gold-quartz deposits	0.2–2200
Skarn deposits	0.2–0.5
Polymetallic deposits	0.2–10
Quartz-pebble conglomerate deposits (Rand)	<0.2–0.7
Disseminated deposits (Carlin, Nevada)	<0.2–0.6 (Radtke *et al.*, 1972*a*) (av. 0.02) (Harris and Radtke, 1976)

Gold combines with tellurium to form a number of hypogene tellurides and telluride-sulphides of which the most common are sylvanite, calaverite, krennerite, montbrayite, petzite and nagyagite. Native tellurium and a variety of other Pb, Ni, Co, Fe, Ag, Hg and Bi tellurides and telluride-sulphides, including tetradymite, tellurbismuth, joseite, hedleyite, altaite, hessite, aguilarite, frohbergite, melonite, rickardite and coloradoite, commonly accompany gold in all types of its deposits. When tellurium forms no minerals in gold deposits the element is camouflaged in a number of sulphides and sulphosalts, particularly galena, stibnite, bismuthinite, lead sulphosalts and tetrahedrite-tennantite. At Yellowknife up to 1000 ppm Te was found by the writer in the galena of the gold ores, up to 100 ppm in stibnite and up to 100 ppm in the lead sulphosalts. The maximum amount of tellurium recorded in the literature for tetrahedrite (goldfieldite) is 17 per cent. Goldfieldite, however, appears to be a mixture, according to some authors and hence requires further study. Native gold frequently contains some tellurium, commonly as admixed tellurides, but probably also as a lattice constituent in some samples.

Native gold is commonly closely associated with the various tellurides and telluride-sulphides in hypogene deposits, but the paragenesis of these minerals is often complex. Generally speaking, however, the tellurides and gold are usually the latest minerals to be deposited in the mineralization sequence. Forsythe (1971) noted a decrease in the Au/Ag ratio with increase in depth in the main ore shoot of the Crown-Crescent lode in the Emperor Gold Mine, Fiji, which he attributed to vertical zoning of gold-silver tellurides caused by a complex deposition sequence, resurgence of mineralization and replacement phenomena. The details of his scheme should be consulted in the original paper.

Berzon and Karyshev (1973) have investigated the Te/Se ratios in the gold deposits of the Urals and have grouped the deposits as follows: (1) gold-sulphide-quartz and gold-quartz-sulphide veins with high Se and Te in the sulphides and an overall ratio of 0.6; (2) gold-selenium-sulphide-quartz veins in which the Se and Te are mainly in the late sulphides; the Te/Se ratio in these deposits is 0.02; and (3) gold-telluride-sulphide-quartz veins, stockworks and silicified zones in schistose rocks; the Se and Te are in late minerals, particularly tetradymite, tellurbismuth and Au-Ag tellurides. The Te/Se ratio is 4. The last are the principal auriferous deposits in the Urals.

Tellurium generally shows a positive correlation with gold (and silver) in most auriferous deposits, and there is commonly a positive correlation between Te, Bi, Au and Ag. In some deposits the correlations are erratic apparently because of the occurrence of abundant native tellurium and Hg, Pb, Fe and Ni tellurides containing little if any gold. In some deposits in volcanic terranes there may be a positive correlation between Te and V. The reason for this circumstance is obscure. There does not seem to be any relationship between the tellurium content of auriferous deposits and their age. Many Precambrian deposits are telluriferous, as are also numerous Tertiary deposits; the latter appear, however, to be more generally telluriferous than the former according to my data.

The supergene minerals of tellurium include the native element; tellurite and paratellurite, TeO_2; montanite, $Bi_2TeO_6 \cdot 2H_2O$; teineite, $CuTeO_3 \cdot 2H_2O$); emmonsite, $Fe_2Te_3O_9 \cdot 2H_2O$; rodalquilarite (chlorotellurite of iron); quetzalcoatlite, $Cu_4Zn_8(TeO_3)_3(OH)_{18}$; and a large number of poorly differentiated Pb, Bi, Cu, Hg, Zn and Mn tellurites and tellurates that occur as ochers and crusts, often intermixed with a great variety of other supergene minerals.

The oxidation states of tellurium of interest in supergene processes are minus (II), (0), (II), (IV) and (VI). The minus (II) state prevails in the tellurides, the (0) state is represented by native tellurium, the (IV) state by the oxide and various tellurites and the (VI) state by the tellurates. Chemically tellurium is similar to selenium in some respects and somewhat like antimony in a few features, particularly its tendency to combine readily with gold and silver. The geochemistry of tellurium, especially its behaviour during supergene processes in gold deposits, is very poorly known (Vlasov, 1966–1968). The writer's research on the element can be outlined as follows:

The common oxides of tellurium, TeO_2 and TeO_3, are both insoluble in water but are amphoteric dissolving in acids and bases. The acids are tellurous, H_2TeO_3, and orthotelluric, H_6TeO_6 or $Te(OH)_6$, all soluble in water. Orthotelluric acid is much different in its ionization properties from those of the corresponding sulphur and selenium acids, and it has a strong tendency to polymerize to form metatelluric acid often characterized as $(H_2TeO_4)_{(n)}$. The salts of tellurous acid are the tellurites and those of telluric acid the tellurates. The dissolved species in acid solution are H_2TeO_3 and H_6TeO_6 and their ionization products. In strong acid solutions TeO_2 forms the positive ion $[TeOOH]^+$. In basic solutions the ions are TeO_3^{2-}, TeO_4^{2-} and their hydrolysis products.

Tellurium forms a sulphate, $TeSO_4$, which is soluble in solutions containing H_2SO_4. The element also readily forms an elemental colloid and may be present in some natural near surface waters in this state. In addition, a number of soluble inorganic complexes are known, and metal-organic and chelate complexes are a feature of the organic chemistry of tellurium, suggesting that the element may migrate in some near surface waters bound to humic and other organic compounds.

The behaviour of tellurium during the oxidation of gold-bearing deposits is varied. In some places the tellurides are relatively resistant to oxidation and pass into the gossans, weathered debris and soils and ultimately into placers as minute corroded crystals and masses. In other places intensive oxidation yields native tellurium, tellurite or a variety of relatively rare Bi, Cu, Pb, Hg, Fe, Zn and Mn tellurites and tellurates. The details of the formation of these minerals are not well known. It would seem from our investigations that oxidation of hypogene native tellurium, tellurides and other tellurium-bearing minerals yields mainly tellurous acid and soluble tellurites where the oxidation potential is relatively low. Under conditions of higher oxidation potential telluric acid and soluble tellurates are produced. Hydrolysis of solutions containing tellurous acid and soluble tellurites appears to precipitate tellurite or paratellurite, TeO_2, close to the primary tellurides or native tellurium, and fixation by ferric ion, hydrous ferric oxide and a number of cations such as Cu, Zn and Mn precipitates insoluble tellurites of which the most common are emmonsite, $Fe_2Te_3O_9 \cdot 2H_2O$; mackayite, $FeTe_2O_5(OH)$; and blakeite, $Fe_2(TeO_3)_3$. Soluble tellurate is also fixed by ferric iron, hydrous ferric oxide, or cations such as Bi, Cu, Pb, Hg, Zn and Mn as various tellurates that are poorly differentiated as minerals. Adsorption of tellurite and tellurate by hydrous ferric oxides and hydrous manganese oxides, and coprecipitation and/or adsorption and absorption by a variety of secondary minerals such as jarosite and beudantite, are also features that tend to restrict the mobility of tellurium in zones of oxidation. Where chloride is present in the system the chlorotellurite of iron, rodalquilarite, may form in the oxidized zones of gold deposits (Lopez *et al.*, 1968). In a number of gold deposits oxidation of tellurium-bearing minerals appears to result in relatively little migration of tellurium, and in this respect the gold and tellurium contents may remain relatively constant or show only a slight sympathetic enrichment or depletion. This is evidently what took place at Cripple Creek, Colorado according to Lindgren (1933). There, the oxidation of the tellurides yielded dark brown powdery gold, colourless tellurite, and ferric tellurites like durdenite and emmonsite; some of the tellurium was carried away in solution. At Carlin, Nevada Radtke *et al.* (1972*a*) noted no particular change in the tellurium content between the 'primary ores' and the 'oxidized ores'. At Yellowknife, Sudbury and elsewhere in Canada the gossans commonly show an enrichment in tellurium as shown by the analyses in Table 39. Where highly acidic conditions prevail or large volumes of water, regardless of pH, pass through the oxidized zones, much tellurium is removed. Under these conditions gold and tellurium appear to part company. Downward migrating tellurium on entering the zone of reduction may be incorporated in the secondary sulphides, in which it may again be enriched with gold. Supergene tellurides are rare in most oxidized auriferous deposits, but in some oxidized telluride-bearing veins small amounts of secondary (probably supergene) tellurides have been noted in local zones of reduction.

As noted above tellurides tend to resist oxidation and may pass into eluvial and alluvial placers together with gold. A variety of tellurides, including joseite, hessite, petzite, sylvanite, krennerite, tellurbismuth, wehrlite, hedleyite, tetradymite, altaite and nagyagite, have all been found in small amounts in the heavy concentrates of various placers in Canada, U.S.A., U.S.S.R. and elsewhere.

Group VIB: Cr, Mo, W

Chromium is a minor and trace constituent of a great variety of minerals found in the various types of gold deposits. In the skarn-type most of the chromium is present in chlorite, biotite, magnetite, ilmenite, pyrite, garnet and numerous other Ca-Mg-Fe silicates. In gold-quartz and polymetallic deposits most of the chromium occurs in minerals such as chlorite, biotite, sericite, pyrite, magnetite and leucoxene. In the conglomerate type, chromium is present mainly in the micas (sericite) and pyrite, with small amounts and traces in a variety of other minerals including chromite which appears to be an original resistate (placer) mineral in the Rand ores (Liebenberg, 1955; Feather and Koen, 1975). The chromium content of the Rand ores appears to range from 585 to 710 ppm (Table 35). Von Rahden and Urli (1969) found a high correlation between Cr, Zr and Ti in some of the reefs of the Rand. In the disseminated gold ores of Carlin, Nevada, chromium occurs in amounts ranging from 7 to 200 ppm (Radtke *et al.*, 1972*a*). This is a considerable enrichment over that found in the carbonate host rocks (7–70 ppm Cr).

Much of the chromium in gold-quartz and gold-bearing polymetallic deposits appears to be inherited from the host rocks, although in places there may be an introduction or remobilization of the element. In skarn-type deposits some of the chromium appears to have been introduced or remobilized from the host rocks. As far as I have been able to ascertain there is no particular correlation between chromium and gold in any of the auriferous hypogene deposits.

Mariposite, the chromium-bearing variety of phengite, and fuchsite, the greenish chromium-bearing variety of muscovite (sericite), are commonly developed in the wall-rock alteration zones and ores of gold-quartz and polymetallic deposits, generally where they traverse serpentine, peridotite and basic volcanic and plutonic rocks. Examples are widespread in the Mother Lode system of California; in Canada at Yellowknife, Timmins, in the Kerr Addison Mine, Kirkland Lake district, Ontario, in British Columbia and elsewhere; in Australia at Kalgoorlie; in a number of deposits in U.S.S.R. in amphibolites and other basic rocks and in some of the auriferous deposits of Taiwan (Chen and Lee, 1974). Other occurrences and various details of the two minerals are discussed by Whitmore *et al.* (1946). The development of mariposite and fuchsite is always intimately associated with carbonatization, especially ankeritization. During this type of alteration the chromium released by carbonatization of chromium-bearing minerals such as serpentine, amphibole, pyroxene, biotite and chlorite is taken up mainly by the alteration micas (sericite) and to a lesser extent by pyrite and arsenopyrite. Some chromium is also transferred to the veins and lodes where it enters pyrite, arsenopyrite and the micas. Studies by the writer on chromium in the Yellowknife and Kerr Addison deposits show that pyrite and arsenopyrite may contain up to 100 ppm Cr; the fuchsite averages about 1600 ppm Cr. Analyses in the literature indicate that some varieties of fuchsite may contain up to 5 per cent Cr_2O_3 and mariposite up to 1 per cent Cr_2O_3.

Fuchsite and mariposite are frequently closely associated with rich gold shoots, and the two green micas can often be considered as good indicators. However, the association is not invariable, there being large stretches of shear zones and altered basic rocks in many deposits with plenty of fuchsite or mariposite but only traces of gold.

During wall-rock alteration processes the behaviour of chromium is variable as shown by Tables 44 to 59 inclusive. In some places there is an enrichment of chromium in the highly altered phases; in others no change or a slight decrease. In basic and ultrabasic rocks the changes can be followed with a fair degree of accuracy. As the rocks containing chromiferous silicates, magnetite, ilmenite, chromite, etc. are subjected to carbonatization and hydration, much chromiun is released since the element cannot be accommodated in the carbonates. It finds a home, however, in chlorite where this mineral is formed or in fuchsite and/or mariposite where these minerals appear in the equilibrium assemblage. The chromium that is left over is accommodated in part in leucoxene, but some appears to migrate upward, together with Al, SiO_2, K and Na, in the vein systems where they may form an abundance of chromiferous micas in the higher level silicified zones and quartz veins.

In nature the most stable states of oxidation of chromium are (III) and (VI); the former state is present in chromite and in the various chromiferous silicates including fuchsite and mariposite; the latter state is present predominantly as chromate (CrO_4) groups in the relatively rare chromates.

During oxidation of chromium-bearing gold deposits much of the chromium in minerals such as fuchsite, mariposite and pyrite appears in the hydrolysis products (limonite, wad, kaolin, etc.) probably as the hydrous sesquioxide, $Cr_2O_3 \cdot nH_2O$, which is readily coprecipitated and/or adsorbed by hydrous iron, alumina and other hydrolysates. The chromium contents in the limonite of gossans are highly variable ranging from 50 to 1000 ppm or more according to my investigations. In the gossans of the Vermilion Mine at Sudbury 125 ppm Cr was found compared with 1250 ppm in the primary ore, indicating leaching of the element during oxidation. On the other hand, at Yellowknife in the Lynx prospect gossan 50 ppm Cr was found compared with 10 ppm in the primary ore. Radtke *et al.* (1972*a*) found chromium contents ranging from 15 to 700 ppm (av. 60 ppm) in the oxidized mineralized ores of the Carlin deposit in Nevada. This indicates only a slight enrichment, if any, over the primary ores which range from 7 to 200 ppm Cr (av. 60 ppm). Under conditions of high oxidation potential some chromium is delivered to the oxidizing solutions probably as soluble alkali or calcium chromates. Where lead minerals are present in the ores, or dissolved lead occurs in the supergene solutions, the mineral crocoite, $PbCrO_4$ may appear, but it is rare. Other species of mineral chromates and dichromates with K, Na, Mg, Pb and Zn, are, likewise rare. Species of phosphate, arsenate and vandate minerals with chromium as an essential element are also known, but these occur only locally. More generally one finds traces to minor amounts of chromium in the common phosphates and arsenates. At Keno Hill, for instance, the pyromorphite in the oxidized zones contains up to 1000 ppm or more Cr. Greenish and purplish coloured chromium-bearing sulphates may occur in the dry parts of the oxidized zones of some gold deposits containing abundant fuchsite, mariposite and other primary chromium minerals. These sulphates are relatively rare and appear to be temporal, dissolving readily with any influx of water.

Few chromium minerals have been recorded in the oxidized zones of auriferous deposits. In some of the Beresovsk veins, Urals, U.S.S.R., crocoite, $PbCrO_4$, occurs with limonite in cavities in quartz near the surface. Pyromorphite is asociated with the chromate in some of the veins.

Few details are available on the concomitant behaviour of gold and chromium during oxidation processes. The writer's limited investigations suggest little change or a slight sympathetic enrichment of the two elements in some gossans. In others, gold is enriched and much chromium is leached, and in still others there is a general loss of both elements as at the Vermilion Mine at Sudbury. There are no recorded instances of a sympathetic enrichment of chromium and gold in the secondary sulphides in the zones of reduction.

Chromite, chromiferous magnetite and leucoxene, chrome micas and a variety of other chromium-bearing minerals accompany gold in some fossil and recent eluvial and alluvial placers. As far as I have been able to ascertain there is no particular correlation between gold and chromium in placers, a feature that one might suspect since most of the chromium-bearing minerals are contributed by the host rocks and not by the hypogene gold deposits.

Molybdenum is commonly associated with gold in most types of its deposits, but the element is generally present only in small amounts. Molybdenite is the only common hypogene molybdenum mineral found in gold deposits. Traces of molybdenum may also occur in some of the sulphides and in scheelite in gold deposits. Our analyses of ores from the various types of gold deposits show the following ranges in molybdenum content in ppm:

Skarn deposits	<1–500
Gold-quartz veins	2–840
Polymetallic deposits	2–840
Quartz-pebble conglomerates (Rand)	2.5–3

In the skarn, gold-quartz and polymetallic deposits, gold is only rarely found in direct association with molybdenite. The paragenesis of the two minerals is, therefore, often difficult to establish. In most deposits where relationships can be clearly ascertained the molybdenite is an early mineral, contemporaneous with quartz. Gold and gold tellurides are generally later than the quartz and, therefore, later than molybdenite. Only occasionally has the writer seen gold intergrown with molybdenite in gold deposits. This confirms Lincoln's (1911*b*) earlier observations. In a few auriferous deposits molybdenite appears to be a very late mineral occurring along post-ore fractures. This age of molybdenite may be younger than the last generation of gold and gold tellurides although the paragenetic relationships are difficult to establish.

The molybdenum content of the disseminated gold ores of Carlin, Nevada ranges from <2 to 100 ppm (Radtke *et al.* 1972*a*).

There are no references to enrichment of molybdenum in gold-bearing precipitates from thermal waters in New Zealand or elsewhere.

Saager (1968) and Feather and Koen (1975) mention the presence of molybdenite in the Rand ores. Our analyses of typical ores from the Rand (Table 35) show molybdenum to be present in the range of 2 to 3 ppm. Those of the Blind River–Elliot Lake district are a little higher in molybdenum content (11 ppm).

In some gold deposits there is a positive correlation between molybdenum and gold as can be seen from the table given by Thomson (1950, p. 97) for the Kirkland Lake ores. In other gold veins the correlation is weak, negative or nonexistent. For example, in one of the Crestaurum veins near Ryan Lake at Yellowknife the molybdenum (molybdenite) content increases as the vein progresses into the granite; concomitantly the gold values drop from a third of an ounce or more per ton (10.8 ppm) to very low values (0.145 ppm).

The common oxidation states of molybdenum are (II), (III), (IV), (V) and (VI). Only the (IV) and (VI) states are of importance in nature, the former occurring in molybdenite, MoS_2, and the latter in a number of rather rare molybdates, including powellite, wulfenite, koechlinite, lindgrenite and ferrimolybdite, all generally supergene minerals. An indefinite oxide, probably $Mo_3O_8 \cdot nH_2O$, called ilsemannite or molybdenum blue, also occurs in the oxidized zones of certain molybdenite deposits.

The oxide MoO_3 is acidic and dissolves in basic solutions to form a complicated series of oxyanions called molybdates, the simplest of which is probably MoO_4^{2-} or some similar hydrated species. When alkaline molybdate solutions are acidified, and the pH lowered below 7, a most complicated series of condensed polymolybdate ions are formed. These have been variously categorized, but no particular consensus appears to prevail among investigators as to their true nature. The hydrates $MoO_3{\cdot}2H_2O$ and $MoO_3{\cdot}H_2O$ can be precipitated from approximately neutral solutions of molybdates. These are not definitely known in nature, although they may be constituents of certain molybdenum ochers. When molybdate solutions or a suspension of MoO_3 are reduced, a deep blue oxide (ilsemannite?) of variable composition $MoO_{2.5\text{-}3.0}$ is formed. According to some investigators this oxide has colloidal properties and is characterized by a defect structure. MoS_2 is precipitated in a hydrated form when H_2S reacts with slightly acid solutions of molybdates.

The alkali and Mg molybdates are soluble; the Ca, Ba, Ag, Pb, Cu, Bi and Fe molybdates are insoluble or sparingly soluble. The complex chemistry of molybdenum is extremely intricate and fraught with many difficulties of interpretation. Most of the complexes are anionic and often polymeric. The element also forms a number of chelates in the laboratory, suggesting that this feature of its chemistry may be important in natural organic environments.

Molybdenite tends to oxidize slowly and in some deposits, especially those characterized by a quartz gangue and a paucity of pyrite and other sulphides, passes relatively unchanged into the eluvium and ultimately into the stream sediments. Under conditions of intense oxidization, particularly in the presence of pyrite and other sulphides, the molybdenum in molybdenite is oxidized to the hexavalent state and enters solution as molybdate or polymolybdate. In this form it probably migrates as the relatively soluble K, Na and Mg species or as the so-called molybdic acid H_2MoO_4. There is also the possibility of migration as a sulphate complex of the type $MoO_2{\cdot}SO_4$.

In a few places the colloidallike hydrous oxide, natural molybdenum blue or ilsemannite, is precipitated close to concentrations of molybdenite. This defect oxide appears to form as the result of the hydrolysis of acidic solutions of soluble molybdates or molybdic acid. More generally the secondary minerals formed are ferrimolybdite where soluble iron is present, or powellite, wulfenite, koechlinite or lindgrenite where Ca, Pb, Bi or Cu are respectively present in the oxidizing solutions.

Ferrimolybdite forms in acid solutions through reaction of ferric iron with soluble molybdates. According to Vinogradov (1957) and others, ferrimolybdite has maximum stability between pH 3 to 4. Jones (1957) gives a pH of 2.7, and Sarafian and Furbish (1965) give a pH of 3.35. In a more acid environment it tends to dissolve and in a more alkaline environment it hydrolyzes according to the equation

$$Fe_2(MoO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2MoO_4$$

This suggests that at the pH of most natural waters (5–8) ferrimolybdite is unstable, and much of the molybdenum present in the mineral passes into solution and is ultimately dispersed. Some molybdenum may, however, be retained as an adsorbed constituent on limonite, and some may be incorporated in secondary minerals such as jarosite, pyromorphite and wad.

Powellite has maximum stability in the pH range from 5 to 6 and wulfenite is probably also most stable in this range. Data on the solubility of the other natural molybdates are lacking.

From the above it is evident that under mildly acidic conditions in oxidized zones there is a relatively high retention of molybdenum in insoluble minerals. Under conditions of high acidity much molybdenum enters solution and is dispersed. The same is true where the waters are neutral or alkaline. Lindgren (1933, p. 64), for example, mentions that the water from a tunnel in the Gilpin County gold mines contained nearly 8 g/L of molybdenum oxide (5332 ppm Mo), and that the water had a deep greenish blue colour. Some of the soluble molybdenum migrating downward in auriferous deposits may be precipitated in the zones of reduction (secondary sulphide zones) probably as colloidal or very fine-grained MoS_2.

In some oxidized zones I have noted that the contents of gold and molybdenum show little change; in others gold is enriched and molybdenum is extensively leached. In the gossans of the Lynx prospect at Yellowknife the molybdenum content averages about 8 ppm as compared with the primary ore which averages about 11 ppm. The corresponding gold values are 0.175 and 0.045 ppm respectively. Radtke *et al.* (1972*a*) report a range of <2 to 50 ppm Mo (av. 7 ppm) in the oxidized ores of the Carlin deposit in Nevada. This indicates little change in the molybdenum content during oxidation processes, since the primary ores contain from <2 to 100 ppm Mo (av. 7 ppm). There is a slight enrichment of gold in the oxidized zones at Carlin. Gold and molybdenum may show a slight enrichment in the zones of reduction of some deposits where secondary sulphides are concentrated.

The writer has observed molybdenite in the heavy concentrates of stream sediments near molybdenite deposits, but has not found the mineral in the heavy concentratres of gold placers. Traces of molybdenum are, however, common in the heavy mineral concentrates of gold placers, the element being probably present in pulverulent molybdenite or in sulphides and other minerals such as pyrite, apatite, and monazite.

Tungsten is a nearly universal associate of gold in its hypogene deposits, a coherence considered by Foster (1977) to be due in part to the similar solubilities of scheelite and gold. I have found the element in practically all of the gold ores that I have examined, the contents ranging from a few parts per million to 5000 ppm or more in some gold-quartz veins.

The principal hypogene tungsten mineral in gold deposits is scheelite. Wolframite and its varieties, such as ferberite and hubnerite, are less frequent but in places may be relatively abundant.

The largest amount of tungsten appear to occur in the skarn-type gold deposits and in gold-quartz veins. Gold-bearing polymetallic deposits generally have low amounts of the element, but some deposits are notably enriched. The Geological Survey's analyses of ores from the various types of auriferous deposits show the following general ranges:

Skarn-type deposits	2–1000
Gold-quartz veins	2–5000
Polymetallic deposits	<2–1000

Rich shoots of scheelite or wolframite may occur in all of these gold deposits. Some have been mined for their tungsten content. The grade of these shoots is generally low, ranging from 0.05 to 0.75 per cent WO_3. In some gold veins, ore shoots rich in scheelite are commonly relatively low in gold.

In the skarn, gold-quartz and polymetallic deposits gold is only rarely found in direct association with scheelite and wolframite. the paragenesis of the tungstates and gold is, therefore, often difficult to establish. In most deposits where relationships can be clearly ascertained the tungstates are early minerals, contemporaneous with quartz. Gold, in a few deposits seen by the writer, occurs as inclusions in scheelite and also along fractures in the mineral. Gold tellurides exhibit similar relationships in some deposits.

Tungsten is enriched in the disseminated gold ores of Carlin, Cortez, Getchell and Gold Acres in Nevada (Roberts *et al.*, 1971). The tungsten content of the Cortez deposit averages about 35 ppm (Wells *et al.*, 1969). Radtke *et al.* (1972*a*) record tungsten contents ranging from <20 to 400 ppm in primary ores of the Carlin deposit. The mineral forms of the element are not stated in the published accounts. Tungsten is, likewise, enriched in the gold-bearing precipitates from thermal waters in the Taupo volcanic zone, New Zealand (Weissberg, 1969). In these precipitates tungsten contents up to 3 per cent have been recorded.

Relatively little is known about the distribution of tungsten in the auriferous conglomerate deposits. Liebenberg (1955), Saager (1968) and others make no mention of the presence of scheelite or wolframite in the Rand ores and analyses of uraninite concentrates from amalgam barrel residues given by Liebenberg show only doubtful traces of tungsten. Analyses of typical Rand ores confirm that tungsten is present in nondetectable amounts (Table 35). In the Blind River–Elliot Lake ores tungsten is, likewise, present in low amounts (2 ppm).

The aqueous chemistry of tungsten is intricate because of the number of oxidation states that the element manifests, (II), (III), (IV), (V) and (VI). Of these only the (IV) and (VI) states are of interest, the former occurring in the mineral tungstenite, WS_2, and the latter in scheelite and other tungstates. During oxidation processes the hexavalent state predominates in the various reactions. This state, represented by the canary yellow oxide WO_3, has a most complicated chemistry many features of which are relatively uncharacterized. In general the chemistry of hexavalent tungsten is much like that of hexavalent molybdenum.

The oxide, WO_3, occurs as tungstite, $WO_3{\cdot}H_2O$, in nature. It is acidic and dissolves in basic solutions to form a complicated series of oxyanions called tungstates, the simplest of which is probably $[WO_4]^{2-}$ or some similar hydrated species. The normal alkali metal and magnesium tungstates are relatively soluble in water; the other metal tungstates are insoluble or only sparingly soluble. These include a variety of supergene minerals of which the most common are stolzite. $Pb(WO_4)$, raspite, $Pb(WO_4)$, cuprotungstite, $Cu_2(WO_4)(OH)_2$, ferritungstite, $Ca_2Fe_2(WO_4)_7{\cdot}9H_2O$, tungsten-powellite, $Ca(Mo,W)O_4$, anthoinite, $AlWO_3(OH)_3$, sanmartinite, $ZnWO_4$ and thorotungstite, an indefinite thorium-aluminum tungstate. There are in addition a number of yellow tungsten ochers, often found in oxidized zones containing hypogene tungsten minerals. These are amorphous to X-rays but are probably various tungsten oxides, hydrous oxides and tungstates.

Scheelite and wolframite tend to resist weathering and solution and generally pass into the gossans and oxidized zones of gold deposits relatively unaffected. Ultimately these minerals pass from the eluvium to stream placers where they are concentrated with gold. Under some conditions, however, especially where the oxidizing waters contain abundant dissolved Na, K or Mg salts or where sulphuric acid is present in abundance from oxidizing pyrite both wolframite and scheelite are slowly dissolved, yielding probably the soluble tungstates and the so-called tungstic acid:

$$CaWO_4 + 2Na^+ = Ca^{2+} + Na_2WO_4$$
$$CaWO_4 + H_2SO_4 = CaSO_4 + H_2WO_4$$

Neither of these soluble compounds have much mobility, especially the acid. It hydrolyzes readily, precipitating tungstite, $WO_3{\cdot}H_2O$. Where the solutions are alkaline the soluble tungstates possess some mobility. Acidification of these solutions, however, yields tungstite on hydrolysis. Where they come into contact with Pb, Cu, Zn, Al, Th and Fe minerals or ions in solution a variety of insoluble minerals noted above may be precipitated. Hydrous iron oxides also coprecipitate and/or adsorb tungstate forming the tungstate, ferritungstite.

The oxidation of gold deposits containing tungsten minerals, therefore, generally leads to accumulations of the resistate tungsten minerals, insoluble secondary tungstates or limonite enriched in tungsten. In this respect tungsten and gold behave in a similar manner and tend to show little change or some enrichment in the oxidized zones. In some deposits tungsten may be leached out of the oxidized zones leaving enrichments of gold. This is what obtains in the gossans of the Lynx prospect at Yellowknife where the tungsten and gold contents of the primary ore and gossans are as follows:

	Primary ore	Gossan
	(ppm)	
W	4	2
Au	0.045	0.175

Radtke *et al.* (1972*a*) noted no marked change in the tungsten content during the oxidization of the disseminated ores of Carlin, Nevada. There are no recorded cases of concomitant enrichment of gold and tungsten in the zones of reduction containing secondary sulphides (Gannett, 1919).

As noted above, scheelite and wolframite resist weathering and solution and pass with gold into eluvial and alluvial placers. Raspite, the lead tungstate, may also accumulate in gold placers. Generally the amounts of the tungsten minerals in gold placers are low and not economic. However, placers are known where both gold and tungsten minerals may be greatly enriched. The Dublin Gulch gold placers of the central Yukon provide such an example (Fig. 69). In the eluvial placers the tungsten content (mainly in scheelite with some wolframite) is 0.5 per cent or more. Parts of the alluvial placers have a similar tenor of tungsten, although these placers as a whole probably only contain about 1/10 as much tungsten. The source of the gold and tungsten in Dublin Gulch is multiple – most of the gold derives from arsenopyrite-pyrite-jamesonite-quartz veins; the wolframite and some of the scheelite comes from stringers of quartz in a nearby granitic stock; and the bulk of the scheelite is weathered mainly from skarn bodies surrounding the stock (Boyle, 1965*a*).

Group VIIA: F,Cl, Br, I

Fluorine accompanies gold in all types of deposits but generally only in small amounts, except in some deposits where fluorite or topaz are important gangue minerals. The most common hypogene fluorine mineral in gold deposits is fluorite. Other hypogene fluorine-bearing minerals include fluormicas, tourmaline, topaz, fluorapatite and a great variety of common silicates such as chlorite, apophyllite, sphene, amphibole, etc. with a small fluorine component. Minerals such as cryolite, and the various rare-earth, U, Nb and Ta fluoride-bearing minerals are extremely rare or nonexistent in gold deposits.

Table 40. Fluorine and chlorine contents of various gold ores

Type of deposit	F	Cl
	(ppm)	
Skarn	1150 (av.)	200 (av.)
Gold-quartz	10–2100	100–500
Polymetallic	10–1000	100–500
Quartz-pebble conglomerate (Rand)	5–195	15–250

Analyses of ores from the various types of gold deposits (Table 40) show the content of fluorine to be relatively low in most places. Where fluorite is a major gangue mineral, as in the Cripple Creek, Colorado deposits the amount of fluorine may exceed 5 per cent (10% fluorite). Similarly, where topaz is an important gangue (alteration) mineral as in the Brewer Gold Mine, Chesterfield County, South Carolina (Peyton and Lynch, 1953) the fluorine contents may run up to 3.5 per cent or more with long core lengths of 1 per cent or more.

Fluorite is not mentioned in the literature as a gangue mineral in the disseminated gold ores of Carlin and elsewhere in Nevada, and Radtke *et al.* (1972*a*) give no analyses for the element.

Analyses of gold-bearing thermal waters in the Taupo volcanic zone in New Zealand contain from 4 to 9 ppm F (Weissberg, 1969).

The fluorine content of the quartz-pebble conglomerates appears to range widely from about 5 to 195 ppm F (Table 35). Most of the fluorine is in the micas and apatite; also in monazite and other Th, U and rare-earth minerals in the Elliot Lake ores.

The behaviour of fluorine in the wall-rock alteration zones of a number of auriferous deposits is shown in Tables 44 to 59 inclusive. The wall-rock alteration zones in deposits in sediments and granites commonly show increases in their fluorine content as the auriferous mineralization is approached; deposits in greenstones, diorites and similar rocks show no change or only slight increases toward the veins.

Fluorite is relatively insoluble in water (16 ppm at 18°C) as are also the fluorapatites (20 ppm at 18°C). Carbonated solutions and mineral acids such as H_2SO_4 dissolve fluorite and apatite slowly yielding fluoride ion, which migrates mainly as the alkali species. The same agents release fluoride ion from fluor-micas and other fluoride-bearing minerals.

In some gold deposits, especially those containing abundant calcium-bearing carbonates, or where Pb, Ca or Al are present in solution, insoluble fluorides, chloride-fluorides and basic fluorides such as secondary fluorite, matlockite, creedite, etc. may be precipitated. Some fluoride may also be adsorbed and/or coprecipitated by hydrous ferric oxides, wad or hydrous alumina complexes, particularly the last. More generally, however, much fluoride is leached from gossans and oxidized zones leaving only trace or minor amounts in these materials. Gold and fluoride, therefore, tend to part company during the oxidation of deposits, gold becoming enriched in the gossans and oxidized zones and the fluorine being largely removed. This is the situation at Cripple Creek, Colorado as described by Lindgren and Ransome (1906). The gossans at the Lynx prospect, Yellowknife exhibit a slight depletion in their fluoride content (30 ppm) compared with the primary gold-bearing quartz-pyrite ore (40 ppm).

Fluorite and fluorapatite occur as minor constituents in some eluvial and alluvial gold placers, and fluorine is generally present in tourmaline, topaz, micas and other silicates in these deposits. Fluoriferous rare-earth, Y, U, Nb and Ta minerals such as yttrofluorite, microlite and pyrochlore may occur in some gold placers, but they are rare.

Chlorine is a constituent of most gold deposits, but the element is invariably present only in small amounts as shown by the analyses in Table 40. Most of the chlorine in gold deposits occurs in chlorapatite and as NaCl and KCl in liquid inclusions in a great variety of minerals, particularly quartz and carbonates. Chlorine-bearing minerals such as the sodalite group, the scapolites and eudialite are rare or nonexistent in most gold deposits. Scapolite occurs in a few skarn-type gold deposits, but it is generally a minor mineral in the gangue.

The writer (Boyle, 1961*a*) made an extensive investigation of the distribution of chlorine (chloride) in the Yellowknife gold-quartz deposits. There, the contents of Cl in the host rocks, alteration zones, and gold ores were about the same (200 ppm Cl, av.). Much of the chloride occurs in carbonates as shown in the following:

Carbonate	Cl
	(ppm)
Ankerite in carbonate-sericite schist (principal gold stage)	50
Calcite and ankerite in cross-cutting quartz-carbonate veins (minor gold in places)	900
Scalenohedral calcite in late fractures (barren of gold)	100

Much of the chloride ion in the carbonates is extractable by pulverizing the minerals and leaching with distilled water. This suggests that the chloride ion is contained in minute inclusions of sodium or potassium chloride in the carbonates, or in these salts in crystal cavities (liquid inclusions).

The behaviour of chlorine (chloride) in the wall-rock alteration zones of a number of gold-bearing deposits is shown in Tables 44 to 59 inclusive. Some of the profiles show little change in the chloride content through the alteration zones, others show some leaching of chloride in certain alteration phases, and still others exhibit small enrichments in some phases.

Gold is soluble as chloride complexes $[AuCl_2]^-$, $[AuCl_4]^-$, etc. as discussed in the section on natural waters in Chapter II. This has led a number of investigators to assume that gold migrates in this form during hydrothermal processes. As noted previously these complexes are stable only in acid solutions below a pH of about 6. At neutral and alkaline pH the concentration of the aurous and auric chloride complexes is insignificantly small. Helgeson and Garrels (1968) have assumed that gold is transferred in acid (pH 2–4) hydrothermal sodium chloride solutions as the aurous chloride complex, but this mechanism has been criticized by Boyle (1969*c*) on several grounds, some of which are mentioned in Chapter II. Gold may be transported in acid sodium chloride solutions, and some gold-quartz veins particularly those containing alunite may have been precipitated from such solutions, but they must be rare considering the small amounts of chloride present in most gold deposits (Table 40) and the general abundance of carbonates in gold veins, minerals that are not readily precipitated from acid solutions with pH 2 to 4. More pertinent, however, is the fact that most present day thermal waters carrying and depositing gold, while containing relatively large amounts of Cl (up to 3000 ppm), are neutral or slightly alkaline. These waters also contain considerable amounts of S, Sb and As, the elements with which gold (and silver) are most commonly associated in nature. It would seem on thermodynamic evidence that gold in such waters is transferred mainly as the $[AuS]^-$ complex or as various other complexes of S, As and Sb as postulated in Chapter II. Weissberg (1970) has concluded from experimental work and from the natural gold-bearing water systems in the Taupo volcanic zone in New Zealand that "The experimental evidence indicates that the most effective gold transport in aqueous sulfide solutions occurs in near-neutral pH solutions containing a high proportion of sulfide as HS^- ions. In more strongly acid or alkaline solutions, where the sulfide species present are dominantly H_2S or S^{2-} respectively, the solubility of gold is much lower and these solutions also seem less likely to play an important role in the hydrothermal transport of gold from the geological point of view."

Seward (1973) concluded, however, that gold is probably transported as both thio and chloro complexes. In near-neutral and alkaline media he thought that three thio complexes were largely responsible for the solubility of gold – the complex $[Au_2(HS)_2S]^{2-}$ in alkaline media, the complex $[Au(HS)_2]^-$ in neutral media and possibly the complex $[Au(HS)]^0$ in acid media.

Before leaving the hypogene processes of gold deposition from chloride solutions it is interesting to note that present day waters in faults in many auriferous regions are charged with chlorides, mainly NaCl. At Yellowknife such waters contain up to 11 383 ppm Cl and occur at a depth of 2300 ft and more (Boyle, 1961*a*, p. 168). Others have recorded similar chloride-rich waters in Precambrian rocks at Timmins, Ontario (Langford and Hancox, 1936), in the Sturgeon River Gold Mine near Nezah in Ontario (Bruce, 1941*b*); in the Kalgoorlie goldfields, Australia (Simpson and Gibson, 1912); and elsewhere. All of these waters have a neutral to alkaline pH. They have been considered to be connate waters by some investigators, but they differ substantially from sea water in having low magnesium contents. In fact their Ca/Mg ratios are usually the reverse to what one finds in sea water. Their origin is enigmatic; they may represent fossil hydrothermal solutions of metamorphic derivation, but this is only a guess.

The alkali and alkaline-earth chlorides are soluble, and their migration is relatively independent of pH and Eh conditions such as those that prevail during oxidation of gold deposits. Oxidation of most types of gold deposits, therefore, generally leads to a marked removal of chloride. In certain types of gold deposits, however, especially those containing an abundance of primary Ag, Pb, Bi, Hg and Cu minerals a number of relatively insoluble chlorides, oxychlorides, complex chlorides and compound chlorides may develop in the oxidized zones and gossans, viz. chlorargyrite, AgCl, calomel, HgCl, cotunnite, $PbCl_2$, eglestonite, Hg_4OCl_2, mendipite, $Pb_3O_2Cl_2$, matlokite, PbFCl, bismoclite, BiOCl, atacamite, $Cu_2(OH)_3Cl$, boleite, $Pb_9Cu_8Ag_3Cl_{21}(OH)_{16}\cdot H_2O$, and kleinite, $Hg_2N(Cl,SO_4)\cdot nH_2O$. Most of these minerals are developed in oxidized zones in hot arid regions or where special conditions prevail such as where the groundwaters are highly saline or where deposits occur near the sea.

Under most conditions in a humid temperate climate, oxidation of gold deposits generally leads to removal of chloride from gossans and oxidized zones. The gold content may show little change, enrichment or depletion depending on the chemical system (*see* Chapter IV). In a hot arid climate oxidation may lead to a sympathetic enrichment of gold, silver and chloride in the gossans and oxidized zones of deposits containing primary Ag, Pb, Bi, Hg and Cu minerals.

Bromine and *iodine* are probably present in most gold deposits, but the amounts would seem to be very low. I have no data on the distribution of these elements in gold ores, but investigations described in the literature indicate that the general levels of abundance of the two elements in mineral deposits are respectively: Br – 0.3 to 5 ppm; I – 0.1 to 1.5 ppm.

Both bromine and iodine occur in some of the gold-bearing thermal waters of the Taupo volcanic zone in New Zealand. Weissberg (1969) records the following ranges in these waters: Br – 3 to 7.2 ppm; I – 0.4 to 2.4 ppm.

The chemistry of bromine and iodine is essentially the same as that discussed for chlorine in oxidation processes. In most humid temperate climates bromine and iodine are extensively leached from gossans and oxidized zones; in hot arid climates Br and I may replace Cl in the chlorides, and the bromide and iodide analogues of some of the chloride minerals mentioned above may form where the primary ores contain Ag, Pb, Bi, Hg and Cu. Of these the most common are bromargyrite, AgBr, and iodargyrite, AgI. Bromates are not known in nature, but in environments where a very high oxidation potential prevails iodates, hydrous iodates, basic iodates, iodate-oxychlorides and iodate-chromates of Cu, Ca and Pb may develop. They are rare.

Group VIIB: Mn, Re

Manganese generally accompanies gold in hypogene deposits mainly in the form of manganiferous carbonates, particularly ankerite. Rhodochrosite and occasionally rhodonite, johannsenite and inesite are important gangue minerals in some gold deposits, principally the gold-quartz and polymetallic types of Tertiary age. Various other manganiferous minerals accompany gold in its deposits including sphalerite in vein and polymetallic deposits, magnetite in a variety of deposits and various manganiferous silicates in skarn deposits. In the auriferous quartz-pebble conglomerate deposits only minor amounts of manganese are present (Table 35), principally in pyrite, sphalerite, chlorite and other minerals.

Certain auriferous quartz deposits are marked by the presence of amethyst, especially those of Tertiary age, which also contain an abundance of manganese minerals. The colour of this amethystine quartz is disputed, but a number of investigations, including those of the writer, suggest that the colouring is due at least in part to manganese ions in the lattice of the quartz.

The behaviour of manganese during wall-rock alteration processes in gold deposits is discussed in a later section. Most of the manganese in the alteration zones and in gold ores appears to have been contributed by the nearby host rocks, although in some deposits contributions from more distant sources are indicated.

The supergene manganese minerals are varied and frequently difficult to determine because they occur in earthy forms and are commonly intermixed with a great variety of other supergene minerals. Pyrolusite, MnO_2, and a great variety of other oxides, hydroxides, basic oxides and oxide-silicates, all intermixed in an aggregate usually called wad, are characteristic of gossans and oxidized zones. There are also a number of phosphates and sulphates that may appear in oxidized zones, but these are usually rare.

The aqueous chemistry of manganese is particularly intricate as befits an element with all oxidation states from (II) to (VII). Since space dictates brevity here, only a brief and relatively simple outline will be given of the fate of manganese during oxidation processes.

Oxidation of most hypogene manganese minerals such as the carbonates yields the aquo complex $[Mn(H_2O)_6]^{2+}$ to solutions. This ion is stable in acid and neutral solutions, and migrates mainly as the sulphate or hydrogen carbonate complex. In alkaline solutions the hydroxide is precipitated, then oxidizes rapidly in the presence of oxygen, water is split out, and MnO_2 (pyrolusite) is formed.

$$2\,Mn(OH)_2 + O_2 = 2\,MnO_2 + 2H_2O$$

Alternatively, the aquo manganous complex is oxidized to the Mn^{4+} state in solution and undergoes hydrolysis with the precipitation of a variety of oxides and basic oxides depending on the pH, Eh and presence of various cations. MnO_2 (pyrolusite) is often the most common of the oxides formed, but it is invariably mixed with a great variety of substances constituting wad.

The formation of gossans and oxidized zones containing supergene manganese minerals is a most complicated problem not readily summarized here. One can contrive Eh-pH diagrams and equations for the iron and manganese systems, but these are generally misleading in their simplicity since it is impossible to take into account all of the phases present, the nonstoichiometric substances formed, the colloidal reactions and the influence of SiO_2, Al_2O_3, PO_4^{3-}, SO_4^{2-}, AsO_4^{3-} and a host of cationic complexes that undergo a most intricate history of hydrolysis reactions. Nevertheless, some general features are evident. Some limonitic gossans are relatively free of large amounts of manganese minerals even though the primary ore and gangue are highly manganiferous. This is probably explained by the fact that comparing the Fe(II) and Mn(II) states the former is more easily oxidized at a lower pH than the latter. Thus, in waters leaching sulphide deposits most of the iron is precipitated as limonite well below a pH of 5 whereas the manganese still retains considerable mobility. Numerous cases of this have been observed by the writer. At Keno Hill, where the pH of the oxidizing waters leaching sulphides and manganiferous siderite averages 6.5, the iron content ranges from 1 to 5 ppm whereas the manganese content frequently exceed 25 ppm (Boyle, 1965*a*).

Under these conditions much manganese is leached, especially from the near surface parts of the oxidized zones. In other deposits, however, the oxidized zones are rich in both limonite and wad or rich in wad with considerable amounts of iron removed, despite the fact that the Eh and pH conditions are such that one might expect a high retention of iron and considerable loss of manganese. The reasons for this type of behavior are not at all clear to this writer. Obviously some uncharacterized chemical factor is at work, perhaps inorganic or organic complexing which renders iron more mobile than manganese.

The presence of supergene manganese minerals, particularly the various hydrous oxides and soluble species of manganese in the oxidized zones of deposits, are important in the migration of gold in three respects. Firstly, the oxides tend to adsorb and/or coprecipitate gold from solution (*see* also the discussion in the section on gold in other minerals in Chapter II). Secondly, Mn(IV) ion has sufficient potential to oxidize gold and render it mobile if complexing agents for gold are present. On the other hand Mn(II) ion reduces soluble gold to the metal. Thirdly, manganese dioxide, and some of the other oxides, aid in the formation of chlorine which complexes with gold and renders it mobile. Thus HCl (derived mainly by the reaction of H_2SO_4 with NaCl or other chlorides in oxidized zones) acting on MnO_2 yields Mn^{2+} and liberates Cl_2 which renders gold mobile as the chloride complex. The various reactions probably run as follows:

$$H_2SO_4 + 2NaCl \rightarrow 2HCl + Na_2SO_4$$
$$4HCl + MnO_2 \rightarrow MnCl_2 + 2H_2O + Cl_2$$
$$Au + Cl_2 \rightarrow \text{Soluble complexes such as } [AuCl_4]^-$$

We see, therefore, that in the absence of chlorides gold tends to be enriched in oxidized zones containing supergene manganese minerals. Where chlorides and an ample supply of H_2SO_4 are available, gold may be mobilized and may migrate downward to the zone of reduction where some of the element may be precipitated in the native state or incorporated in the secondary sulphides. The remainder of the element migrates in the groundwater system and is ultimately lost from the deposits.

It should also be mentioned that the presence of manganese in natural waters, especially surface waters, seems in places to be responsible for the relatively high migration capacity of gold. The precise reasons for this behaviour are unknown – one factor seems to be that gold is adsorbed to the various hydrous manganese oxide colloids and is carried in this manner; another may be adsorption and/or incorporation of gold in suspended humic manganese colloids.

Manganese is a constituent of a great many light and heavy minerals that accompany gold in recent and fossil eluvial and alluvial placers. In some placers manganese is a major constituent of limonite-wad cemented gravels, sand and silt. These materials, as well as gravels and sands that contain an abundance of limonite-wad particles, are invariably enriched in gold, probably largely as a result of adsorption processes.

Rhenium is a very rare element that occurs in amounts of a few parts per million or less in a number of minerals, principally the sulphides, molybdenite, pyrite, chalcopyrite, bornite, sphalerite and galena. It is often enriched in molybdenite in which it may be present in amounts from <1 to 3000 ppm or more according to analyses quoted in the literature. Three poorly differentiated rhenium minerals are known, but these are extremely rare. Of these the sulphide, dzhezkazganite, ReS_2, is probably the most common. The geochemistry of the element is discussed by Vlasov (1966–1968) and Ivanov *et al.* (1972).

Speaking generally, it can be said that rhenium follows Mo and W in hypogene processes, and in places there appears to be a coherence with Cu, Pb, Cd, Zn, and perhaps with Se, Te and U.

There are only a few data on the content of rhenium in gold deposits. Ivanov *et al.* (1972) mention rhenium contents ranging from 0.02 to 0.86 ppm in pyrite from some gold-bearing deposits in U.S.S.R. The writer has detected the presence of rhenium in molybdenite in some gold deposits but only in small amounts (~ 10 ppm).

During oxidation processes rhenium appears to be more mobile than molybdenum (Morachevskii and Nechaeva, 1960). The element, once liberated from its hypogene host minerals, mainly molybdenite, probably migrates as the perrhenate ion, ReO_4^-, in the form of the soluble calcium or sodium salt. In chloride waters it may also migrate as the soluble ReO_3Cl compound (Mukanov and Aubakirova, 1969). Perrhenate ion does not form highly insoluble salts with the cations of Ca, Pb, Sr and Fe, as does the molybdate ion, a feature that further increases its mobility with respect to molybdenum. The perrhenate ion is to some extent adsorbed by hydrous iron oxides, but the effect of manganese oxides is uncertain; it is probably coprecipitated with manganese because of the chemical similarities of the perrhenate and permanganate ions. In most places wads are in general low in rhenium. Potassium-bearing supergene minerals such as jarosite probably concentrate rhenium because of the low solubility of potassium perrhenate.

One can only speculate that rhenium is retained in some degree in the gossans during the oxidation of gold deposits, but where extensive leaching has taken place probably much of the element is removed. Since rhenium forms a sulphide readily (ReS_2, dzhezkazganite), certain zones of reduction (secondary sulphides) may be enriched in the element, although there are no data available to suggest that this in fact does take place.

Group VIII: Fe, Co, Ni and Pt group metals

Iron is a constant companion of gold in all types of its deposits. There is no need to belabour the details of this marked association, but a few points should be stressed. The principal hypogene iron minerals accompanying gold in its deposits in their order of abundance are pyrite, arsenopyrite, pyrrhotite, ankerite, siderite, chalcopyrite, bornite, magnetite and ilmenite. To these can be added a veritable host of iron silicates, particularly biotite, chlorite, epidote, hornblende, amphibole, etc. In nearly all deposits gold, gold tellurides and aurostibite are later than these iron minerals in the paragenetic sequence.

The behaviour of iron during the wall-rock alteration processes that attend gold deposition is discussed in a later section of this chapter. As McKinstry (1957) has pointed out, much, if not all of the iron, bound in sulphides and carbonates in gold deposits, is derived locally from the host rocks. Some of the iron delivered to solutions through leaching of iron-bearing rocks may migrate considerable distances as witnessed by the fact that iron sulphides and other iron minerals are common constituents of the precipitates found at the orifices of auriferous hot springs.

The fate of iron during the oxidation of sulphides, carbonates, silicates, etc. in gold deposits is a most complex problem that can be treated here only in a general outline. The oxidation states of interest are Fe(II) and Fe(III), the former occurring in sulphides, carbonates and most silicates, and the latter in some silicates, in magnetite and in hematite, limonite, a variety of basic salts and a host of other supergene minerals.

When iron sulphides, carbonates, silicates, etc. are subjected to the action of meteoric waters, iron is initially released as the aquo ferrous ion $[Fe(H_2O)_6]^{2+}$ which migrates mainly as the sulphate, hydrogen carbonate complex, $[Fe(HCO_3)_2]$, chloride or as a number of organic complexes usually referred to collectively as humates for lack of exact characterization. The oxidation potentials are such that ferrous ion can be converted to ferric ion in acid solution by the oxygen of the air. The conversion is slow or inhibited in very acid solutions ($pH<2$). Change in pH through the neutral point into the alkaline range results in the precipitation of ferrous hydroxide, which is readily oxidized to the brown hydrous ferric oxide in air. Ferric iron in the absence of complexing agents is present as the aquo ion $[Fe(H_2O)_6]^{3+}$. The principal feature of this ion is its marked tendency to hydrolyze, to enter a variety of basic salts, and to form complexes. To prevent hydrolysis the pH of the solutions must be acid ($pH \sim 0$); with increasing pH (circa 2) extensive hydrolysis sets in, and at a pH of 2 to 3 condensed polynuclear species appear, and ultimately gelatinous $Fe_2O_3 \cdot nH_2O$ is precipitated. But this is a gross oversimplification of what actually takes place in nature when SO_4^{2-}, PO_4^{3-} and AsO_4^{3-} are found in solution in the presence of ferric ion, K, Na, Pb, Zn, Ag and other metal ions. In this situation as the pH increases a veritable host of basic salts may appear such as jarosite, pharmacosiderite, cacoxenite, beudantite, etc. These, however, tend to be unstable to extensive leaching by meteoric waters, and some of their constituents pass into solution leaving ferric iron as limonite. Under other conditions a number of normal ferric salts may form, some of which are relatively insoluble, examples being scorodite and a number of phosphates.

Oxidation of gold ores containing iron-bearing sulphides and other minerals invariably leaves a residue of limonite (gossan) in which scorodite and/or the basic salts may be developed. Pyrite, the iron carbonates and other iron-bearing minerals first yield ferrous iron to the solutions that may oxidize to ferric iron, and this in turn undergoes hydrolysis with the precipitation of hydrous iron oxides (limonite) or basic salts, or minerals such as scorodite, depending on the pH and the availability of various cations and anions. Alternatively, ferrous hydroxide may be precipitated, then readily oxidized, yielding hydrous ferric oxides (limonite). Iron passing downward in the deposits may be precipitated in the zone of reduction mainly as marcasite or pyrite. Gold may be enriched in the limonitic parts of gossans, in the zones of scorodite and/or basic salts and in the zone of reduction. More is said about these enrichments in Chapter IV.

The presence of supergene iron minerals, particularly the hydrous oxides, and soluble species of iron in the oxidized zones of deposits is important in the migration of gold in two respects. Firstly, the oxides tend to adsorb and/or coprecipitate gold from solution (*see also* the discussion in the section on gold in other minerals in Chapter II). Secondly ferric ion has sufficient potential to oxidize gold and render it mobile, provided complexing species such as chloride are present. On the other hand, in the absence of complexing species, ferrous iron reduces soluble gold to the metal. The interplay of all these reactions is complex and is discussed in more detail in Chapter IV.

It should also be mentioned that the presence of iron in natural waters, especially surface waters, seems in places to be responsible for the relatively high migration capacity of gold. The precise reasons for this behaviour are unknown – one factor seems to be that gold is adsorbed to the various hydrous iron oxide colloids and is carried in this manner; another may be adsorption and/or incorporation of gold in suspended humic iron colloids.

Iron is a constituent of a great many light and heavy minerals that accompany gold in recent and ancient eluvial and alluvial placers. The most abundant heavy iron mineral in gold placers is magnetite; ilmenite is common in some placers, and pyrite is ubiquitous but is generally present in small amounts. In some placers iron is a major constituent of limonite-wad cemented gravels, sand and silt. These materials, as well as gravels and sands that contain an abundance of limonite-wad particles, are frequently enriched in gold, probably largely as a result of adsorption processes.

Cobalt accompanies gold in most types of deposits but generally only in trace or minor amounts. In most deposits cobalt is a constituent of pyrite, pyrrhotite, pentlandite, magnetite, chalcopyrite, arsenopyrite and tennantite-tetrahedrite in which it is usually present in amounts up to 100 ppm. Smaltite, cobaltite, safflorite, linnaeite and other cobalt sulphides and arsenides are relatively rare in gold deposits, but a few gold-quartz veins and skarn deposits containing some of these minerals are known in the Middleburg district, northern Transvaal; in the French Mine, Hedley, British Columbia; in the Windpass Mine, British Columbia (Uglow and Osborn, 1926); in some of the gold-quartz deposits at Ramore, Ontario; and elsewhere. The Ni-Co-Fe arsenide veins (Cobalt, Ontario type) with abundant native silver generally contain only traces of gold (<10–100 ppb).

The cobalt content of the Rand ores appears to range from 37 to 102 ppm (Table 35). In these ores gold is often associated with cobaltite, gersdorffite, skutterudite and linnaeite which it either replaces or with which it is intergrown (Pelletier, 1940; Liebenberg, 1955; Feather and Koen, 1975). These sulphides are mainly secondary (remobilized) and late in the paragenetic sequence according to Liebenberg. According to Feather and Koen (1975) both cobaltite and gersdorffite occur in two distinct generations, one detrital and the other authigenic. The detrital variety of these two solid solution minerals is essentially cobaltite whereas the authigenic variety associated with the main period of gold remobilization is gersdorffite. Feather and Koen also showed that the order-disorder relation of the authigenic cobaltite-gersdorffite and the mixed crystal compositions in the system FeAsS-CoAsS-NiAsS can be used as a sensitive indicator to estimate the temperature at which the reefs have been elevated during the period of metamorphic activity that remobilized the gold and precipitated the associated secondary minerals. Their results indicated a temperature in the region of 600°C for most reefs.

The disseminated gold deposits of Nevada, U.S.A. (Carlin, Cortez, Getchell and Gold Acres) are not characterized by marked enrichments of cobalt (Wells *et al.*, 1969; Roberts *et al.*, 1971); in fact some of the highly mineralized limestones at Cortez are depleted in the element. At Carlin, however, Radtke *et al.* (1972*a*) found a slight enrichment (<2–50 ppm) in the primary ore as compared with the fresh carbonate rocks (<2–7 ppm). In the 'oxidized ores' they found from <2 to 150 ppm Co.

Weissberg (1969) makes no mention of the presence of cobalt in the gold-rich silica-sulphide precipitates from thermal waters in the Taupo volcanic zone, New Zealand.

The fate of cobalt during oxidation processes has been extensively studied by the writer and his colleagues (Boyle and Dass, 1971*a*). Only some of the details need be reiterated here.

The oxidation states of cobalt of interest are (II) (cobaltous) and (III) (cobaltic). The former occurs in a variety of sulphides and arsenides (e.g., linnaeite, Co_3S_4; smaltite, $CoAs_2$), in the carbonate, cobaltocalcite $CoCO_3$, and the arsenate, erythrite, $(Co,Ni)_3(AsO_4)_2 \cdot 8H_2O$. The (III) state occurs in various ill-defined cobaltic oxides and hydrous oxides of which stainierite (heterogenite), CoO(OH), is fairly well differentiated.

The aqueous chemistry of cobalt (II) is dominated by the formation of the aquo ion $[Co(H_2O)_6]^{2+}$ and its many ionic complexes. Unlike ferrous ion, the cobaltous ion is relatively stable to oxidation. Addition of a base yields $Co(OH)_2$ whose pH of precipitation is approximately 6.8. The hydroxide exhibits colloidal and gel properties. It is amphoteric yielding the cobaltous ion in acid solutions and the ion $[Co(OH)_4]^{2-}$ in concentrated alkali. Hydrated cobaltous salts with the most common anions are known, and many of these are relatively soluble, particularly the sulphate, chloride and nitrate. The carbonate is insoluble but exhibits increased solubility with increased amounts of CO_2 in solution, probably because of the formation of the hydrogen carbonate complex $Co(HCO_3)_2$. Arsenate ions precipitate the insoluble arsenate, erythrite, and sulphide ions or H_2S precipitate an insoluble sulphide from cobaltous solutions. Trivalent cobalt is unstable as the free

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aquo ion $[Co(H_2O)_6]^{3+}$, since it is reduced by water to the cobaltous state. The reduction is less marked in basic than in acid media. In its many complexed forms, however, cobaltic ion is relatively stable to reduction. Hydrolysis of cobaltic solutions leads to the precipitation of indefinite hydrous oxides; one species CoO(OH) appears to be a definite compound. Cobaltic oxide is also formed by the oxidation of freshly precipitated $Co(OH)_2$. The hydrous cobaltic and cobaltous-cobaltic oxides have colloidal and gel properties.

The oxidation of cobalt sulphides, arsenides and other primary cobaltian minerals yields cobaltous ions to meteoric waters, and these migrate mainly as the hydrogen carbonate, sulphate, chloride or as soluble organic complexes. Where arsenic is abundant in the environment complex hydrolytic reactions lead to the precipitation of erythrite and other arsenates, under midly acid, neutral or slightly basic conditions. Locally, where evaporation of the solutions takes place hydrated sulphates such as bieberite, moorhouseite and aplowite are precipitated. These are soluble and hence temporal. With increasing alkalinity or by reaction with alkali bicarbonate solutions cobaltocalcite may be precipitated although this secondary mineral is rare. The indefinite hydrous cobaltic and cobaltous oxides appear to originate by oxidation of $Co(OH)_2$, which is precipitated or coprecipitated with ferrous hydroxide, alumina and other oxides and hydroxides in weakly acid, neutral and basic solutions. Where hydrous manganese dioxide is precipitated cobaltian wad (asbolite) may be abundant. Strong adsorption of cobalt to hydrous ferric oxides (limonite) is also a feature of some oxidized gold-bearing sulphide-arsenide deposits containing cobalt. Despite all of these various mechanisms of precipitation cobalt retains a relatively high mobility, and much of the element is leached from the deposits. Some cobalt passing downward into the zones of reduction is precipitated in the secondary sulphides.

Gold and cobalt may be concentrated together under certain conditions in gossans, particularly in those containing abundant wad or limonite-wad aggregates. More generally, however, gold is enriched in the gossans, and cobalt is extensively leached as at the Lynx prospect, Yellowknife and elsewhere (Table 41). Gold and cobalt may again join company and be moderately enriched in secondary sulphides in the zone of reduction.

Cobalt is a trace to minor constituent of a number of heavy minerals that accompany gold in recent and fossil eluvial and alluvial placers. Chief among these are pyrite, arsenopyrite, pyrrhotite, magnetite and ilmenite. In some placers cobalt is a minor or trace constituent of limonite-wad cemented gravels, sand and silt. These materials, as well as gravels and sands that contain an abundance of limonite-wad particles, are frequently enriched in gold, probably largely as a result of adsorption processes.

Table 41. Cobalt, nickel and precious metal contents of some auriferous ores and gossans

	Co	Ni	Pt	Pd	Au
			(ppm)		
Lynx prospect, Yellowknife					
Quartz-pyrite ore	46	5	<0.02	0.03	0.045
Gossan	2	<2	<0.02	0.03	0.175
Vermilion Mine, Sudbury					
Chalcopyrite-pyrite ore	100	8850	35	108	1.9
Gossan	7	312	130	100	0.545

Nickel accompanies gold in most types of deposits but generally only in trace or minor amounts. In most deposits nickel is a constituent of pyrite, pyrrhotite, chalcopyrite, arsenopyrite, tennantite-tetrahedrite and other sulphosalts in which it is usually present in amounts up to 100 ppm. Pentlandite, maucherite, millerite, niccolite, breithauptite, chloanthite and other nickel sulphides and arsenides are relatively rare in gold deposits, but a few gold-quartz veins, polymetallic deposits and skarn deposits containing these minerals are known in British Columbia and Ontario; at Alistos, Mexico (Krieger and Hagner, 1943); at the Mackinaw Mine, Washington, U.S.A. (Milton and Milton, 1958); and elsewhere. A number of these deposits are in or near peridotites, serpentinites and other basic and ultrabasic rocks. An excellent example of this is found at the old Cuniptau Mine, near Goward, Ontario where the auriferous ore contained pyrrhotite, chalcopyrite, pentlandite, violarite, pyrite, sphalerite, magnetite, chromite, calaverite and sperrylite (Sandefur, 1942).

The Ni-Co-Fe arsenide veins (Cobalt, Ontario type) with abundant native silver generally contain only traces of gold (<10–100 ppb). The Ni-Co-Cu ores of the Sudbury type are, likewise, low in gold. Hawley (1962) mentions the extreme rarity of the metal in the Sudbury ores, and found native gold in only one of the deposits. According to our calculations and analyses the Sudbury ores as mined contain on the average about 0.08 ppm Au and 2.5 ppm Ag. The ores of the Norilsk region in U.S.S.R. have about the same content of gold and silver. In the Rand ores gold is associated with pentlandite and gersdorffite in some reefs and with pyrrhotite, arsenopyrite and various cobalt sulphides and arsenides, which contain some nickel in other reefs. These sulphides and arsenides are mainly secondary (remobilized) and late in the paragenetic sequence according to Liebenberg (1955) and Feather and Koen (1975). (*See also* the discussion under cobalt.) The nickel content of the Rand ores ranges from 106 to 158 ppm (Table 35). The disseminated gold deposit at Cortez, Nevada, exhibits a slight enrichment of nickel in the highly mineralized limestone according to the data provided by Wells *et al.* (1969) and Radtke *et al.* (1972*a*). The latter investigators give the range of nickel content as 7 to 200 ppm in the Carlin ores as compared to 1 to 30 ppm in the carbonate host rocks; in the 'oxidized ores' they found 1.5 to 500 ppm Ni indicating some enrichment during oxidation. Weissberg (1969) makes no mention of the presence of nickel in the gold-rich silica-sulphide precipitates from thermal waters in the Taupo volcanic zone, New Zealand.

The fate of nickel during oxidation processes has been extensively studied by the writer and his colleagues (Boyle and Dass, 1971*a*). Only some of the details of interest as they pertain to gold deposits need be mentioned here.

Nickel can assume five oxidation states, (0), (I), (II), (III) and (IV). Only the divalent state is of importance in nature, occurring in various sulphides, arsenides, the oxide, a few hydroxides, a complex carbonate, several arsenates and a number of silicates. The (0) oxidation state is represented by certain natural nickel-iron alloys.

The aqueous chemistry of nickel (II) is dominated by the formation of the aquo ion $[Ni(H_2O_6]^{2+}$ and its many ionic complexes. Unlike ferrous ion and cobaltous ion, the nickelous ion is quite stable to oxidation in natural environments. Addition of a base yields $Ni(OH)_2$, whose pH of precipitation is approximately 6.6. This hydroxide is basic with no amphoteric properties. It exhibits colloidal and gel properties, dissolves readily in acids and also in ammonia with the formation of the complex ion $[Ni(NH_3)_6]^{2+}$. Nickel hydroxides and compound nickel hydroxides are known in nature. Most occur with garnierite. Nickelous oxide, NiO, is formed when water is split out of the hydroxide. It is basic in character, insoluble in water and occurs as the mineral bunsenite.

Nickelous salts with most of the common anions are known, and many of these are relatively soluble, particularly the sulphate, chloride and nitrate. The carbonate, $NiCO_3{\cdot}6H_2O$, which precipitates when alkali bicarbonates are added to nickelous solutions, the phosphate, $Ni_3(PO_4)_2{\cdot}8H_2O$, and the arsenate, $Ni_3(AsO_4)_2{\cdot}8H_2O$, which precipitate under mildly acid, neutral and mildly basic conditions are insoluble. The carbonate, phosphate and arsenate are, however, soluble in strongly acid solutions and sparingly soluble in solutions with excess CO_2, the latter probably because of the formation of hydrogen carbonate complexes. The normal carbonate has not been recognized in nature, but a hydrated basic carbonate, zaratite, $Ni_3(CO_3)(OH)_4{\cdot}4H_2O$, is known. The basic carbonate results probably because carbonate solutions containing nickel hydrolyze readily and precipitate basic carbonates rather than the normal carbonate. The phosphate is not known in nature, but a number of arsenates, of which annabergite is the most common, occur frequently in the oxidized zones of nickel deposits. Two common hydrated sulphates (retgersite and morenosite) are known and a number of silicates of variable composition, collectively known as garnierite occur as oxidation products of nickel minerals.

Addition of H_2S or sulphide ion to nickelous solutions yields NiS, which is extremely insoluble in water.

All oxidation states of nickel are characterized by their ability to form complex ions and compounds of great variety and multiplicity. Some of these such as $[Ni(NH_3)_6]^{2+}$ and various chelates may occur in nature, although they have not yet been characterized.

The oxidation of gold deposits containing nickel minerals yields solutions containing the element mainly as the sulphate, hydrogen carbonate, or as soluble organic complexes. The resultant secondary minerals depend on the type of deposit. In deposits containing nickeliferous sulphides and arsenides, the oxide, basic carbonate, arsenates (mainly annabergite) and hydrated sulphates may appear in small amounts, but the usual product is a nickelian limonite and wad. Where hydrolysis and other reactions take place in a milieu dominated by dissolved silica, silicates or silica gel, the garnierite group of hydroxyl-bearing nickel silicates, may be developed. During the oxidation of most types of gold deposits containing nickel much of the element is removed; some, usually only small amounts, is precipitated in the zone of reduction in the secondary (supergene) sulphides. Comparing cobalt and nickel it is my experience that the former is the more mobile of the two elements, although in some types of deposits both elements exhibit a high mobility, especially in acid solutions (Boyle and Dass, 1971*a*).

Gold and nickel may be concentrated together under certain conditions in gossans as indicated by the data of Radtke *et al.* (1972*a*) mentioned above. The enrichment of nickel is usually greatest in those zones containing an abundance of limonite and wad. More generally, however, gold is enriched in the gossans, and nickel is leached, as shown by the analyses of primary ore and gossan at the Lynx prospect, Yellowknife (Table 41). Gold and nickel may again join company and be moderately enriched in secondary sulphides in the zone of reduction of certain deposits.

Nickel is a trace to minor constituent of a number of heavy minerals that accompany gold in recent and ancient eluvial and alluvial placers. Chief among these are pyrite, arsenopyrite, pyrrhotite, magnetite and ilmenite. In some placers pellets of the nickel-iron alloys may occur especially in the vicinity of serpentinites. Nickel is a minor or trace constituent of limonite-wad cemented gravels, sand and silt in some places. These materials, as well as gravels and sands that contain an abundance of limonite-wad particles, are frequently enriched in gold, probably largely as a result of adsorption processes.

The *platinum* family of elements comprises the light platinoids, ruthenium, rhodium and palladium, and the heavy platinoids, osmium, iridium and platinum. These elements form a number of alloys in nature and are also combined with As, S, Se, Te, Sb, Bi or Sn to form numerous minerals of which the most common appears to be sperrylite, $PtAs_2$. For general reviews of the occurrence of platinoids with gold see the works by Kemp (1902), Mertie (1969) and Cabri (1972).

Some varieties of native gold contain the platinoids, mainly in placers but also in the hypogene deposits and their oxidized zones. The amount and type of the various platinoids in native gold appears to be highly variable, and no generalizations can be made except to say that perhaps palladium is the most common of the platinoids in gold (*see also* the section on gold minerals in Chapter II). Excepting native gold there is no exact knowledge how the platinoids occur in gold-bearing deposits that are enriched in these metals. The elements seem to have an affinity for copper minerals and are frequently concentrated in chalcopyrite, bornite, tetrahedrite-tennantite and chalcocite. Pyrrhotite, pentlandite and various arsenides also contain the elements, especially in the massive Ni-Cu deposits. Pyrite is usually very low in the elements. The Geological Survey analyses, and those of Hawley (1962) and Keays and Crocket (1970), indicate that most sulphides, arsenides, sulphosalts, etc. rarely contain more than a few parts per million, and most have less than 1 ppm, total platinoids. Some of these platinoids may be present in the various sulphide, arsenide, etc. minerals as discrete platinoid minerals, although in many cases they probably substitute for Cu, Ni or Fe. Certainly in some deposits (e.g., Vermilion Mine, Sudbury, Ontario) they are present as minute grains of sperrylite, mitchenerite or froodite. The platinoids have a marked affinity for tellurium and at least three platinoid tellurides are known in nature. This suggests that the platinoids may be present in the gold and other tellurides in some gold deposits.

Concentrations of platinum metals are relatively rare in gold deposits, and the reverse is generally true that gold is generally present only as a trace constituent in typical platinum metal deposits. Gold-quartz veins that we have investigated contain only traces of Pt (<0.005 ppm) and Pd (<0.01–0.05 ppm) as do also the various other types of auriferous deposits that have been studied at the Geological Survey. Mercer and Crockett (1972) found average gold contents of approximately 1.5 ppm and 0.4 ppm respectively for the orebody and adjacent metasediments in the Heath-Steele B-1 deposit, Bathurst-Newcastle district, New Brunswick. The corresponding palladium contents were 0.0014 and 0.0026 ppm.

There are reports that certain quartz veins in Columbia, Finland, U.S.S.R., South Africa, New Zealand and Ontario contain platinoids, but their gold content is not mentioned. Some of those in New Zealand are described by Bell (1906). Those in the Waterberg district of South Africa are described by Wagner (1926). Certain contact metamorphic and other types of unusual skarn deposits are enriched in platinoids and often contain some gold. Examples are known in Brazil and South Africa (Lindgren, 1933, p. 779); also in U.S.S.R. in central Asia where Timofeeva (1972) described auriferous skarns with chalcopyrite, pyrrhotite, arsenopyrite, molybdenite, joseite, tiemannite and Pt-Pd minerals, e.g., niggliite, cupropalladium and sperrylite. Most of the deposits are richer in palladium than in platinum. A number of gold-bearing copper deposits have unusual concentrations of platinoids in places. The Cuniptau Mine at Goward, Ontario (Sandefur, 1942) developed Cu-Ni-Pt-Au ore in a shear zone in Archean serpentinite. The ore consisted mainly of pyrrhotite, chalcopyrite, pentlandite, violarite, pyrite, sphalerite, tetrahedrite, magnetite, calaverite, sperrylite and chromite. The Salt Chuck Mine on Prince Edward Island, Alaska is another example (Mertie, 1921). This mine operated on an ore containing disseminated bornite, chalcocite, covellite and epidote in a pyroxenite. The concentrates averaged about 40 per cent Cu, 1.2 oz/ton Au, 5.3 oz/ton Ag and 3.1 oz/ton Pt and Pd. The ore averaged 0.063 oz/ton Au and 0.253 oz/ton Pt and Pd. Yet another example is cited by Emmons (1903) and Knopf (1915) in the Yellow Pine district, southern Nevada. In this deposit abundant plumbojarosite (a supergene mineral) carried on the average in ounces per ton: Au – 3.46; Ag – 6.4; platinum – 0.70; and palladium – 3.38. The primary ore was siliceous and composed of lead, copper and iron sulphides.

Most epigenetic auriferous vein, replacement, polymetallic and skarn deposits, enriched in platinoids, occur in or near peridotites, pyroxenites, serpentines and other types of ultrabasic rocks, judging from the geological descriptions, some of which are rather inadequate on which to base conclusions. However, it does appear as though these ultrabasic rocks have in some manner or other provided the platinoids; the concentration into the veins, etc. appears to have been largely by a secretion mechanism long after the consolidation of the ultrabasic rocks.

Small amounts of iridosmine containing mainly osmium and iridium and minute amounts of platinum, ruthenium, rhodium and gold are won from the gold ores of the Witwatersrand quartz-pebble conglomerate (Mertie, 1969). A total of about 6000 oz of platinoids is said to be recovered annually from the ores. Geological Survey analyses of the platinoid content of the Rand ores and other quartz pebble conglomerates are given in Table 35. Cousins (1973) gives the value of 0.0035 ppm for the average recovery content of platinoids in the reefs of the Rand and an average Au-platinoid ratio of 2000. The Au-platinoid ratio of the West Rand ranges from 100 to 8000 (Stumpfl, 1974). According to Liebenberg (1955) iridosmine and other platinoids are relatively common in the amalgam barrel residues, but grains of the mineral are rarely seen in the matrix of the bankets. Some of the grains of iridosmine are intergrown with small amounts of native platinum, and the grains of iridosmine are also sometimes partly replaced by gold. Other grains of native platinum with small amounts of Pd, Rh, Ru, Os and Ir are occasionally found in the matrix of the conglomerate. Liebenberg, (1955) and others consider that the platinoid minerals are detrital in origin, but those in the Carbon Leader would seem to have been introduced in a manner other than by sedimentation. (*See* the discussion on the origin of these deposits in the last part of this chapter.) In a recent contribution Feather and Koen (1975) list a great number of platinoid minerals for the Rand of which the most abundant are osmium, iridosmine, osmiridium and iridium. They consider most of these to be detrital, but some, especially the platinoid mineral coatings such as sperrylite and hollingworthite on platinoid alloy grains, are thought to be of secondary derivation. (*See further* the section on the association of platinoid minerals with gold in the next section.)

The gold content of platinoid-rich layers of ultrabasic rocks such as those associated with the Bushveld and other differentiated basic bodies is very low generally in the range of 0.05 to 0.5 ppm according to our analyses. This can be compared with the platinoid-bearing ores of the Merensky Reef in the Bushveld complex, which average about 8 ppm (0.25 oz/ton) total platinoids. The Sudbury and similar deposits associated with ultrabasic and basic rocks, enriched in Ni and Cu, carry very low gold contents, about an average of 0.08 ppm. The total platinoid content of the Sudbury ores appears to range from 0.65 to 9 ppm (0.019–0.26 oz/ton), but the actual tenor varies greatly from place to place and with type of ore (Hawley, 1962). Judging from production figures the respective percentages of platinoids present are Pt, 45 per cent; Pd, 40 per cent, and the remainder of platinoids, 15 per cent. Some deposits seem to depart from these abundances, palladium being more abundant than platinum. Keays and Crocket (1970) found positive correlations between Os-Ru, Os-Ir and Ru-Ir and weak negative correlations between Pd-Ir and Pd-Os, but no correlation between gold and any of the platinoids in some of the minerals and orebodies at Sudbury.

The fate of the platinum metals during the oxidation of deposits in which they are enriched is only imperfectly known. The writer's research on these metals in the surficial cycle is incomplete, and hence some of the statements made below are tentative.

The native platinoid metals, their alloys and native gold containing the platinoid metals do not appear to dissolve to any great extent in most supergene solutions derived from the oxidation of pyrite, pyrrhotite, chalcopyrite and other sulphides or arsenides. Exceptions to this may occur where complexing agents such as thiosulphate, cyanide, chloride and certain organic compounds are present, in which case the gold, silver and perhaps some of platinoids may be dissolved and leached from the deposits. Sperrylite, essentially $PtAs_2$, seems to be relatively resistant to oxidation, occurring in a number of the gossans at Sudbury and elsewhere. It also occurs in some placers. Laurite, $(Os,Ru)S_2$, also appears to resist oxidation in some deposits. The fate of other platinoid arsenides, sulphides, selenides, tellurides, antimonides, bismuthides and stannides during oxidation processes is unknown. Probably some are oxidized, and their constituent platinoids are released to the supergene solutions. The platinoids in substitutional sites in the various sulphides, arsenides, etc. are probably released to the supergene solutions, perhaps in some cases as soluble sulphates (e.g., platinic sulphate) and in others as a variety of soluble complex ions which are especially characteristic of the platinum metals. Palladium seems to be more mobile than platinum during oxidation processes since the Pd-Pt ratio appears to decrease in oxidized zones and gossans compared with the primary ore in some deposits (Table 41). Ruthenium and osmium, likewise, appear to possess considerable mobility during oxidation, probably because they form relatively soluble complex oxy anions. Numerous other factors appear to affect the mobility of the platinoids in a differential way. Thus Pt and Pd in solution appear to be relatively easily reduced to the metallic state by ferrous sulphate (similar to Au and Ag) whereas Ru, Os, Rh and Ir seem to be little affected. Soluble arsenites and arsenates precipitate complex compounds, especially from solutions of Pt and probably Pd. H_2S appears to precipitate all of the platinoids from their solutions as sulphides.

Because platinoids in solution are readily reduced to the metallic state by a variety of reductants they do not generally migrate far in gossans and oxidized zones. The exact nature of the reductants is unknown, but organic matter, ferrous sulphate and residual sulphides appear to be involved. The dissolved platinoids probably follow four main courses. The largest amounts appear to be precipitated on the residual particles of native platinoids in the gossans and in the nearby soils and weathered residuum. Small amounts are either adsorbed and/or coprecipitated by limonite, wad and other colloidal materials or precipitated as an exceedingly fine dust, perhaps composed of various platinoid minerals, with minerals such as limonite, wad, malachite and plumbojarosite. Certain supergene minerals may accommodate the platinoids in their structures although proof of this feature is lacking as yet. The occurrence of high platinoid assays in oxidized zones of some deposits containing plumbojarosite and other basic sulphates suggests that these minerals may carry some of the platinum metals as lattice constituents. The fact that solutions of Ru, Rh, Pd, and Pt sulphates can precipitate basic and complex oxy-sulphates tends to support this contention. Finally, small amounts of the dissolved platinoids are transported downward in oxidized zones and are concentrated at lower levels in secondary (supergene) sulphides, particularly chalcocite and covellite. The nature of the platinoids associated with these sulphides is unknown.

The resultant of all these processes is that the platinoids tend to be enriched in most gossans and oxidized zones in the form of the native metals and alloys, or as sperrylite, and probably other platinoid minerals. Assays of some of the gossans at Sudbury recorded in the early literature show up to 10 oz/ton of platinoids whereas the general average of fresh sulphide ore in this area is about 0.1 oz/ton of platinoids. Gold, and frequently silver, exhibit a parallel enrichment with the platinoids in some gossans and oxidized zones, particularly those rich in jarositic minerals, developed on Ni-Cu and other platinoid-bearing deposits. These two precious metals are, likewise, enriched with the platinoids in supergene sulphide zones, especially those rich in copper where chalcocite and covellite are developed. Part of the enrichment of gold with platinoids in supergene environments probably involves the potentials of free metals; thus platinum metal will reduce and/or coprecipitate gold from solution, as can be seen from their position in the electrochemical series.

Gold is frequently accompanied in placers by platinoid minerals, particularly the alloys, but also by sperrylite and occasionally other platinoid arsenides, bismuthides, etc. The platinoids generally appear with gold in placers principally in terranes where serpentinites and other ultrabasic rocks or platinoid deposits of the Bushveld or Sudbury type are present.

> Le quartz est le plus fidèle compagnon de l'or
> —Cumenge et Robellaz (1898)

Mineral associates of gold

Mention is made in the previous section of the great variety of minerals accompanying gold in its deposits. Here we shall consider the most common mineral associates of gold and attempt to show how they differ or remain constant in gold deposits of all types and different geological ages. The paragenetic relationships of the various gold minerals with respect to other metallic and gangue minerals are also discussed. Particularly helpful in the compilation of this section have been the condensed data given by Lincoln (1911*b*), Schwartz (1944), Petrovskaya (1955, 1971, 1973, 1974), Feather and Koen (1975), and Anhaeusser (1976).

A number of native elements and alloylike compounds accompany gold in its deposits. Most of these minerals are present only in small amounts, although a few may be relatively abundant in some deposits.

Graphite, amorphous carbon and *carbonaceous matter,* commonly referred to as 'carbon', are frequently encountered in gold deposits of practically all types. The presence of graphite and amorphous carbon in black and grey quartz and in carbonates is discussed in detail in the sections describing quartz. The carbon minerals also occur in seams and slips and irregular masses along faults and in brecciated parts of the orebodies. Frequently these minerals are greatly enriched in native gold and other gold minerals. It is common for instance to find native gold smeared along graphitic slips in many orebodies. Mention should also be made here of the common occurrence of rich shoots of gold where veins and other deposits intersect graphitic beds – the so-called black leaders or indicators of the old gold miners.

'Carbon' has been of considerable interest to gold miners and metallurgists for many years, principally because it causes severe difficulties in winning the gold from the ores as a result of its precipitating effect on gold in the cyanide circuits. Innumerable descriptions of carbonaceous material in gold deposits appear in the literature. Here we may mention the papers by Bell (1924) on the carbonaceous matter in the Porcupine (Timmins) mines of Ontario; Van Aubel (1936) on the graphitic matter in the auriferous veins of Kivu, Zaire; Boyle (1953) on the carbon and graphite in the quartz of the veins at Yellowknife; Liebenberg (1955) and Feather and Koen (1975) on the 'carbon' of the Witwatersrand, South Africa; Baskakova (1970) on the organic matter in the gold-quartz veins of the Kyzyl-Kum desert, U.S.S.R.; Roberts *et al.* (1971) and Wells (1971) on the carbonaceous matter in the Carlin disseminated deposit, Nevada; Scheiner *et al.* (1971) on various carbonaceous gold ores in United States; and Saxby and Stephens (1973) on carbonaceous matter in the sulphide ores from Mount Isa and McArthur River in Australia. 'Carbon' or graphite occurs in auriferous deposits in all types of rocks including granites. It seems to be most abundant in deposits of Precambrian age diminishing through time and being rare in Tertiary deposits. In the younger deposits, however, bituminous substances may be relatively abundant in some gold belts.

The nature of 'carbon' in gold quartz deposits, mainly of Precambrian age, has been studied in many places by the writer. To summarize, it can be said that much of the 'carbon' is amorphous to X-rays and gives no patterns. Chemically this type of 'carbon' is essentially pure carbon with little if any other constituents such as H,O,P, etc. In some veins, however, the 'carbon' is crystallochemically organized and gives fair to good X-ray patterns for graphite. This 'carbon' or graphite is generally present in zones of high grade metamorphism (amphibolite facies and higher). Other types of 'carbon' are also present in gold deposits. Baskakova (1970) recognized bituminous substances and humic acids in the gold-quartz veins of the Kyzl-Kum desert. The bituminous substances on analysis proved to be hydrocarbons. The 'carbon' in the Rand ores is of two types Liebenberg (1955) – a radioactive variety or thucholite and a nonradioactive variety probably best described as anthraxolite.

Thucholite, carburan and *anthraxolite* are not commonly found in skarn deposits, but the first mineraloid has been recognized in the skarn-type Richardson deposit at Eldorado, Ontario (Boyle and Steacy, 1973). There, the mineraloid contains micro-grains of gold and uraninite distributed throughout the groundmass in no particular pattern. In gold-quartz-sulphide veins thucholite, carburan and anthraxolite are relatively rare, but examples are known from the auriferous Boliden ores in Sweden and the auriferous-uraniferous Box Mine, Nicholson and other ores of the Goldfields (Uranium City) district of Saskatchewan. In the Goldfields occurrences the gold is younger than the thucholite. In the quartz-pebble conglomerate ores of the Rand thucholite (or uraniferous carbon) is abundant and has received considerable study by Davidson and Bowie (1951), Liebenberg (1955), and others. (*See* the section on the Witwatersrand in this chapter.) The thucholite is dull-black in appearance and confined mainly to the conglomerate bands and pyritic quartzites; in places seams and bands of thucholite often mark the lower bedding planes of the conglomerates. The thucholite occurs mainly as small warty granules with a roundish or oval form mainly in the phyllosilicate matrix; irregular patches and stringers are found in places, but they are rare; columnar and massif thucholite occur as streaks or 'pencil lines' to relatively thick layers as in the 'Carbon Leader'. Under the microscope the massive thucholite is composed of aggregates of granules in places separated by narrow rims of gold and gold-bearing sulphides. The columnar variety of thucholite is generally fairly homogeneous; in places gold and sulphides occupy partings between the parallel adjacent columns. The granular type of thucholite has a tendency to be round and oval, and granules often merge into each other to form stringers and irregular masses. Most granules have an authigenic appearance and occupy interstitial spaces in the matrix of the conglomerates. All of the varieties of thucholite contain small grains and minute inclusions of uraninite, up to 150 in a single granule 0.5 mm in diameter. This phenomenon is interpreted by Liebenberg as due to replacement of large grains of uraninite by the hydrocarbon. Some of the specks and veinlets of uraninite in the thucholite are interpreted as secondary. Gold and auriferous sulphides are closely associated with thucholite, occurring as minute inclusions and veinlets in the mineraloid, in bands around the granules in places and in the boundaries between adjacent granules.

Carbonaceous substances other than thucholite in the Rand ores consist mainly of brownish hydrocarbons that contain no radioactive inclusions. Dull, black, nonradioactive carbonaceous matter mixed with chlorite is also common in the Black Reef. Gold is not associated with this hydrocarbon; according to Liebenberg (1955) this carbonaceous matter was introduced at a late stage.

The paragenetic relationships of gold, thucholite, carburan and anthraxolite in auriferous deposits are of interest. In some cases small blebs of gold are scattered at random through the hydrocarbons and seem to be of exsolution origin; in others the gold is late and occupies small cracks and fissures (syneresis cracks) in the hydrocarbons. The late gold may represent exsolution from the hydrocarbons, or it may have been introduced from other parts of the deposits.

The origin of the 'carbon' in gold deposits has long been a subject of speculation. In some deposits, particularly those in carbonaceous and graphitic shales or schists some of the carbon is a residue after replacement as shown by Van Aubel (1936) and others. In other deposits, especially those in volcanic, granitic bodies and conglomerates the carbon has obviously been introduced. Its source is a problem, however, and there has been much speculation on the subject. Bell (1924) hypothesized that:

> The carbon may have been the product of the decomposition of carbonates into carbon dioxide, carbon monoxide and, finally, elementary carbon. No less may it be the product of carbon, precipitated from soluble carbides, or even the result of decomposition of hydrocarbons. Owing to the common close connection of carbon and carbonates in the vein material, one would be tempted to favour the derivation of the former from the latter, were it not for a realization of the difficulties presented by the dissociation of carbon monoxide into carbon and oxygen in ordinary atmospheric temperature and pressure. At the same time it is recognized that these difficulties may be far from insurmountable under geological conditions.

That this is the case has been recently shown by Salotti *et al.* (1971) who discussed the origin of graphite in deposits. They envisage a reaction of the type: carbon mineral + hydrogen → (methane to butane) + water + metal oxide or hydroxide. A subsequent reaction involving the pyrolitic dissociation of methane yields carbon:

$$CH_4 \rightarrow C + 2H_2$$

This mechanism is an attractive one for the derivation of carbon in gold deposits and is supported by some field evidence. Thus, in many deposits in the Canadian Shield and in younger rocks methane, and in places other heavier hydrocarbons, are dissolved in the deep waters that course along the faults and slips. Carbonaceous matter is precipitated with gold in places along these faults probably as a result of the pyrolitic processes mentioned above. The source of the hydrocarbons in young rocks is easily explained, but the presence of methane and other hydrocarbons in Precambrian rocks is a mystery. The writer (Boyle, 1961*a*) once considered them to have come from the surface, but their presence at depths of several thousand feet in some places seems to negate this hypothesis. On the contrary they appear to be coming from great depth, and they may represent some uncharacterized synthesis deep within the earth. They deserve further study, especially as regards the fundamental problem of the origin of petroleum. In the Witwatersrand reefs methane is a common gas, and this has led Liebenberg (1955) to conclude that much of the thucholite and other carbonaceous substances are the result of polymerization of hydrocarbon gases by radioactive emanations. He does not, however, rule out the possibility that oily hydrocarbons in addition to gaseous hydrocarbons took part in the formation of the thucholite. In the Rand the methane and oily hydrocarbons were probably derived from primitive bacterial or algal material that permeated the conglomerates in their depositional sites.

While the gaseous hydrocarbon theory is an attractive one for the origin of hydrocarbons and carbon in gold deposits, there is considerable evidence to suggest that liquid hydrocarbons are the more probable sources of the carbon. Rather than the hydrocarbons replacing uraninite in the Rand bankets, it seems more probable that the uranium and the gold were introduced into the sites by some sort of liquid hydrocarbon-gold-uranium compound. Certainly the distribution of the specks and minute inclusions of uraninite and gold in the thucholite, both in the Rand and in the Richardson deposit, suggests exsolution of these elements from a hydrocarbon gel. In the case of the Richardson deposit the organometallic compound evidently migrated in solution or by diffusion into the skarn where it was precipitated. With time, polymerization processes (actually dehydrogenation and decarboxylation), with splitting out of uranium and gold left an aggregate of thucholite in which uraninite and native gold were dispersed. In the Rand deposits the organometallic compounds evidently absorbed (dissolved) uranium and flour gold from the quartzites, shales and conglomerates, and carried them into porous sites where the aging of the hydrocarbon gels liberated gold and uranium which now appear in, or in the near vicinity of, the thucholite as native gold and uraninite.

In the Rand the story may not be as simple as that just expounded. In a recent contribution Hallbauer and van Warmelo (1974) have examined both the columnar and 'fly speck' types of thucholite from the Carbon Leader Reef and other auriferous reefs by scanning electron microscope. Their results are most interesting. In the columnar type, internal structures morphologically resembling filamentous, branched and apparently septate cells of obvious biological origin were identified. These were partly encrusted with gold. In addition silicified structures, which they identified as primitive fungi, were noted. From these observations they concluded that the organism was some kind of fossilized symbiotic lichenlike plant with no modern equivalent that formed carpetlike colonies of up to several square metres in extent. These organisms were capable of extracting gold and uranium from the environment and depositing them inter- and intracellularly. The 'fly speck' carbon constitutes spherical nodules with irregular and pitted surfaces showing a remarkable morphological resemblance to living fungal *sclerotia* (reproductive hyphae). The amorphous coal-like thucholite is envisaged by Hallbauer and van Warmelo as due to exogenous plant debris washed into its present position and there attacked by a fungal organism. (*See also* the section in the last part of this chapter on the origin of the Witwatersrand deposits.)

In gold-quartz veins and other similar deposits the organometallic (hydrocarbon) compound evidently migrated in solution or by diffusion into the deposits where it was precipitated. With time dehydrogenation and decarboxylation proceeded almost to completion leaving only carbon (graphite) and gold as the residuals.

The question 'What is the precise relationship of gold to graphite and carbonaceous matter in gold deposits?' has been partly answered above. In some deposits at least some of the gold is evidently contemporaneous with the carbon. In other deposits it is obvious that the carbonaceous matter has precipitated some of the gold – the famous black leaders or indicators of Bendigo, Australia and the black bands in the Meguma Group of Nova Scotia are prime examples of this phenomenon.

Diamond and *carbonado* may accompany gold in placers but generally not in economic quantities. Occurrences are widespread: in the gold-bearing gravels of California; in the gravels of Minas Geraes, Bahia and other states in Brazil; in the gold washings of Victoria, Queensland and South Australia; in some of the golden gravels of the Irrawaddy River in Burma; in the auriferous placers of Borneo; in the gold-platinoid placers of the Urals; and elsewhere in many parts of the world. Most occurrences of diamonds in gold placers appear to be in terranes containing kimberlites, lamprophyres and similar rocks or in terranes characterized by ancient conglomerates (fossil placers) which may have initially collected the gold and diamonds. Platinoids are common associates of gold in placers containing diamonds. In general diamonds and gold are not associated in endogenic deposits, kimberlites containing only background amounts of gold (0.005 ppm); gold-quartz and other types of gold deposits are similarly devoid of diamonds.

Sulphur in the native form is not an important mineral in most gold deposits, except in the oxidized zones where it frequently occurs in small amounts, being derived in most places by oxidation of H_2S and polysulphides formed during the oxidation of hypogene sulphides. Where native sulphur occurs in oxidized zones it is commonly accompanied by wires, tufts, hairs, mossy aggregates, spangles, minute crystals and finely divided particles of native gold. Supergene minerals associated with the auriferous sulphur often include gypsum (selenite) and alum. Hypogene sulphur occurs in a number of Tertiary (near surface) gold deposits. An example is the Kasuga deposit in southern Kyushu in Japan (Taneda and Mukaiyama, 1970). There, the sulphur occurs as small irregular blebs, patches and masses in the silicified orebody. Associated minerals are quartz, enargite, luzonite and native gold. The gold appears to be contemporaneous with the native sulphur. In the Chinkuashih gold-copper deposits of Taiwan native sulphur and cinnabar are the last minerals to be deposited (Huang, 1973).

Native *arsenic* is present as an ore mineral in some gold deposits, principally in those of Tertiary age. The mineral is particularly common in the Bau gold district in Sarawak. There, the native arsenic is auriferous, containing gold as microscopic blebs and apparently also as a lattice constituent. The latter feature was studied by Lau (1970) and the writer. Native arsenic also occurs in the ores of Nagyág in Romania, Hauraki in New Zealand, in certain veins in New South Wales, Australia and elsewhere.

Native *antimony* is relatively rare in most gold deposits, generally occurring in those containing abundant antimony minerals. No relationships with respect to the age of deposits have been observed. At Yellowknife (Precambrian) native antimony has been observed in microscopic grains and blebs in massive stibnite in the ores in greenstones. It occurs in a similar manner in the stibnite ores of West Gore, Nova Scotia (Paleozoic). No paragenetic relationships with gold and other gold minerals could be established. The native antimony in auriferous deposits at Lucknow, New South Wales is exceptionally rich in gold (>200 ppm).

Allemontite, AsSb, is a relatively rare mineral in most gold deposits. It has been reported from the Ophir Mine, Comstock Lode, Nevada and from the Engineer Mine at Atlin, British Columbia (Walker, 1921). Some of the pure specimens of allemontite from Atlin are highly auriferous (Table 8). Using the electron probe the nature of the gold in the allemontite could not be determined; it is apparently not present in discrete particles of native gold and hence is probably in the lattice of the mineral.

Native *bismuth* occurs in gold deposits in only small amounts. There appears to be no particular relationships with respect to the age of deposits, although the mineral is not particularly common in Archean ores as far as the writer can ascertain. Gold occurs in native bismuth in the deposits at Tennant Creek and Cobar, Australia (Stillwell and Edwards, 1941, 1942), and some of the Barberton gold deposits in South Africa contain metallic bismuth. At the Windpass Mine, British Columbia, gold and bismuth are associated, and Lowell (1942) says that significant amounts of native bismuth and gold occurred in the ores of the Jewett and Irwin mines in southwestern Oregon. In France, native bismuth is common in the gold-quartz ores of the Salsigne-Aude district (Tollon, 1970). Native bismuth is present in skarn-type gold deposits in many parts of the world. The paragenesis of native bismuth and gold in deposits is often difficult to ascertain. In some deposits their deposition appears to overlap; in others native bismuth is frequently a late mineral, in places later than gold.

Maldonite, the bismuthic gold (Au_2Bi), is probably a mixture of gold and native bismuth, since the compound Au_2Bi is metastable at normal temperatures and hence tends to exsolve or partition into two phases. The mineral occurs at Maldon, Victoria, Australia where it is associated with bismuth minerals, native gold, scheelite, and apatite in veins and greisen veins; also in garnetiferous skarn at Redsbanya, Romania and rarely in the gold-quartz veins of the Salsigne-Aude district in France where it is associated with bismuthinite.

Native *tellurium* is commonly mentioned as being present in gold deposits. It occurs in very small amounts closely associated with various tellurides, pyrite, galena, alabandite, etc. in a number of gold deposits in Romania (Transylvania) and Western Australia (Kalgoorlie). Also in the mines of Balia, Asia Minor, in several gold districts in Japan (Kawazu Mine, Izu Peninsula) and in a number of gold and silver districts in the western United States, mostly in Colorado (Cripple Creek, Magnolia, Goldhill, Ballarat and Central districts, Boulder County; Vulcan, Garfield County; Gunnison County) and at Delamar, Lincoln County, Nevada. The analyses of the mineral quoted by Palache *et al.* (1944) and Chukhrov (1960) all show gold present in minor amounts (0.15–2.78%), probably as an admixture of the metal or as various gold tellurides.

Native *silver* is a rare mineral in the hypogene ores of gold deposits. I have seen it only occasionally in the deposits of the Timmins area and in the Ross Mine, near Ramore; also in the veins of the Berens River area, northwestern Ontario. In the Ross Mine it may belong to a separate stage of mineralization entirely divorced from the gold stage. In the Kidd Creek deposit at Timmins, native silver is abundant in the great massive sulphide orebody. This silver contains only a trace of gold. The massive sulphide ore is, likewise, almost devoid of gold. In the ores of Cobalt, Ontario, native silver is phenomenally enriched, but gold is present only in minute amounts (<10–100 ppb). Native silver is reported in the literature to be present in numerous auriferous deposits in U.S.S.R. and elsewhere. Most of this silver is in the oxidized zones, but some may be in the primary zones and may be of hypogene origin, although the descriptions do not always make this clear.

Native silver, as wires, foils, dendrites, scales, spangles and irregular nodules and masses, is common in the oxidized zones of some gold-silver deposits, especially the 'bonanza' type where the silver is largely present in tetrahedrite-tennantite, argentite and argentiferous galena in the hypogene ores. The chemistry and origin of this native silver is discussed at length by Boyle (1968*b*) and summarized in Chapter IV.

Electrum or *argentian gold* with a ratio of gold to silver of 1:1 corresponds to 36 per cent silver; 2:1 to 21 per cent, etc. Electrum is common in many gold deposits, particularly those of Tertiary age. (*See also* the next section on Au/Ag ratios in deposits and the section on the mineralogy of gold in Chapter II.)

Dyscrasite, the silver antimonide, appears to be very rare in gold deposits so far as this writer has been able to ascertain. Saager (1968) mentions its presence in small amounts in the Rand ores. He thinks it is a detrital (allogenic) mineral introduced with detrital sulphides into the bankets at the time of their formation.

Native *copper* occurs only infrequently as a hypogene mineral in gold deposits. The mineral is occasionally present as small nuggets, irregular masses and sprigs in the quartz veins of the Ptarmigan Mine at Yellowknife, Northwest Territories. Its relationship to the native gold could not be determined. Native copper has also been observed in some veins in the Beardmore area of Ontario, and there are scattered reports of the presence of hypogene native copper in various types of gold deposits in many parts of the world.

Supergene native copper is commonly encountered in the oxidized parts of gold deposits enriched in copper minerals.

The native *platinoids* appear to be uncommon hypogene minerals in auriferous deposits. They probably occur in microscopic amounts in some of the deposits enriched in platinoids, as discussed in the last part of the previous section on elemental associates of gold. Small amounts of iridosmine occur in the ores of the Witwatersrand. According to Liebenberg (1955) some of the grains of iridosmine are intergrown with small amounts of native platinum, and grains of iridosmine are sometimes replaced by gold. Liebenberg considers the platinoids to be of detrital origin, but it would seem that those in the Carbon Leader, including platiniridium, platinum and osmiridium, had an origin other than sedimentation. (*See* the discussion on the origin of the auriferous quartz-pebble conglomerates in the last part of this chapter.)

In a recent contribution to the occurrence, distribution and origin of platinoids in the Rand, Feather and Koen (1975) list the following platinoid minerals as being present in the reefs: osmium, iridosmine, osmiridium and iridium are the most abundant with lesser amounts of isoferroplatinum, ruthenosmiridium, ruthenian iridium, iridian ruthenium, Rh-Pt alloy, sperrylite, hollingworthite, iridarsenite, ruthenarsenite, geversite, michenerite, moncheite, laurite, braggite, cooperite, a palladium telluride and an unnamed mineral with composition RhS_2. They consider the alloys and the isoferroplatinum to be essentially of detrital origin, modified slightly by coatings and overgrowths of secondary platinoid minerals such as sperrylite and hollingworthite.

In recent placers gold is commonly accompanied by small to moderate amounts of native platinoids, particularly in terranes characterized by ultrabasic intrusives or by basic intrusives with associated Ni-Cu-Co sulphide deposits.

Native *mercury* appears to be extremely rare as a hypogene mineral in auriferous deposits. The metal may, however, occur in small amounts in the oxidized zones of gold-bearing deposits containing cinnabar and other mercury minerals. In these situations the metal has been observed occasionally in the gold deposits of Kalgoorlie, Australia, California and the U.S.S.R. Gold amalgam may accompany native mercury in some deposits.

Native mercury, gold amalgam and a variety of indefinite amalgams principally of the platinoids may accompany gold in recent placers. In some cases these minerals seem to have resulted from the escape of mercury from amalgam barrels during former placer mining; in other cases they may be natural.

In oxidized zones and placers gold may be accompanied by a number of metals and unusual alloys, none of which occurs in any quantity. Native *lead* has been reported from the gold placers of the Urals and Altai, from those in Colombia, from certain auriferous stream sediments and soils in the Keno Hill area, Yukon (Boyle, 1976*b*) and from scattered diggings in many parts of the world. Most of these occurrences seem to be authentic, although in some placers the lead may be hunter's shot. Krylova (1975) mentions the presence of native lead in a Mesozoic-Cenozoic gold-silver deposit in the northeastern U.S.S.R. The native metal is associated with pyrite, galena, sphalerite and silver sulphosalts. Native *zinc* occurs both in the oxidized zones of some gold deposits and in various placers, but only sporadically and generally in small amounts. Its origin is somewhat of an enigma (Boyle, 1961*b*). Pellets, grains and plates of *nickel-iron* are relatively common in gold placers, particularly where ultrabasic rocks and basic rocks with associated nickeliferous sulphides are present in the terrane. Occurrences are widespread – in the Fraser and other rivers in British Columbia and Yukon; in the platinum placers of the Urals; in the gold washings of the Gorge River, New Zealand; and in various old placers in western U.S.A. Native *tin* is rare but has been noted in the gold-platinum sands of the Aberfoil and Sam rivers near Oban, New South Wales and elsewhere. Mustart (1965) noted an AuSnPb compound of unspecified name in the gold placers of Bonanza Creek, Klondike district, Yukon. Native *tantalum* is very rare but has been reported from the gold washings of the Urals and Altai Mountains, U.S.S.R. The mineral requires confirmation, since not all investigators agree as to its authenticity.

Quartz is the most common mineral in all types of gold deposits, a fact mentioned in the very earliest writings on the precious metal. Practically all varieties of this mineral are found in gold deposits, including crystalline, massive, cryptocrystalline or chalcedonic and amorphous (silica) (*see* pls. 1–16). The colours cover the spectrum ranging from colourless, white, black, grey, mottled black and white, blue, amethyst, to rose. Citrine (yellow quartz) does not seem to have been recorded in gold deposits. In some deposits the quartz is highly crushed, fractured, brecciated, recrystallized and recemented by later generations; in other deposits the mineral is little affected by shearing, fracturing or recrystallization.

In the writer's experience quartz crystal (rock crystal) occurs in gold deposits of all ages; those of Tertiary age tend to have more of this variety of quartz than do deposits of older epochs. However, some Tertiary deposits are markedly devoid of quartz crystal. The quartz in deposits of Precambrian, Paleozoic and Mesozoic age tends to be massive and highly crushed, fractured, recrystallized, etc. This is evidently due to repeated tectonic activity, although it should be noted that some Precambrian veins examined by the writer are nearly completely devoid of the effects of structural deformation. Cryptocrystalline and chalcedonic quartz, often beautifully banded and alternating with quartz crystals, is characteristic of Tertiary gold deposits wherever they are found. This type of quartz also occurs in some older deposits but is generally relatively rare. Amorphous quartz (silica), concretionary quartz, and sintery quartz is a feature of gold-bearing precipitates at the orifices of hot springs. Wood opal (petrified wood) containing gold occurs in some tuffaceous deposits (*see* page 47). Common opal and agate are rare in gold deposits in the writer's experience. Jasper, prase and chrysoprase are rare in gold deposits but appear in small amounts in places, the first where iron minerals such as hematite are relatively abundant and the last two in rocks rich in nickel minerals such as serpentines.

The colour of quartz in gold deposits is an interesting subject, studied by the writer for many years. In general most of the quartz in gold veins is colourless or white, often milky. The latter when coarsely crystalline with a greasy aspect is known to the prospector as 'bull quartz' or 'buck quartz' and often a sign of poor gold values. In Precambrian rocks this is certainly frequently the case; in younger rocks the criterion does not hold. In fact, some of the richest veins in Paleozoic and Mesozoic rocks are essentially 'bull quartz', but usually highly fractured.

Black and grey quartz owes its colour to two principal causes – electronic darkening due to bombardment by particles or rays emanating from radioactive minerals and colouring due to black impurities such as graphite, amorphous carbon, tourmaline and finely divided sulphides or sulphosalts. The first, electronically darkened or smoky quartz, is relatively rare in gold deposits mainly because of the general absence of uraninite and other radioactive minerals in the deposits. In some deposits, however, such as the Witwatersrand the darkening of the quartz pebbles in some reefs is partly due to this process and partly due to the presence of carbon according to the writer's investigations[22]. Other gold deposits containing pitchblende and other uranium minerals may have smoky quartz, but they are relatively rare. Most black and grey quartz and most of the greyish blue varieties are coloured by amorphous carbon or graphite which forms oriented trains and disseminations along wavy planes or occurs as randomly distributed fine dust throughout the quartz grains (Boyle, 1953). Such quartz is particularly common in Precambrian deposits in practically all types of rocks. It also appears, but not so frequently, in deposits of younger age mainly in those in greywacke-carbonaceous slate-argillite sequences. The exact relationship of the carbon with gold is not clear, but it has been repeatedly observed that when black quartz and white quartz occur in the same specimen, the former tends to contain much more gold. With some reservations it appears as discussed above under the section on graphite, etc. that the gold and carbon are intimately related for one or other of two reasons – the gold was transported by the mother substances (hydrocarbons) of the carbon or the carbonaceous matter acted as a precipitant for the gold.

The source of the carbon in many varieties of quartz is an enigma. In some veins the carbon is obviously relict from the replacement of carbonaceous and graphic sediments; in other veins, especially those in porphyries and volcanics such an origin seems improbable since these rocks rarely contain much free carbon. The carbon may have had a number of possible origins as discussed above under graphite and amorphous carbon. It may represent reduced carbon dioxide, which was obviously abundant during the formation of the veins and which commonly occurs in the liquid inclusions in the quartz. How this was accomplished is, however, not clear because of the high reduction potentials required. The carbon could conceivably represent diffusion or hydrothermal transport of the element in some manner or other into the veins, but we have no exact knowledge of this process. Graphite veins in metamorphic rocks suggest such a process, although there are alternate explanations. One of these, suggested by Salotti *et al.* (1971), involves the interaction of hydrogen with carbonate minerals to produce methane followed by the pyrolitic dissociation of the methane to yield free carbon. Finally, the carbon may represent the final decomposition product of a great variety of hydrocarbons of uncertain origin. Gold may also be transported with the hydrocarbons as some kind of organometallic or chelated compound as suggested by two lines of evidence. Firstly, black quartz is commonly highly enriched in gold, and secondly, gold is intimately associated with thucholite (or uraniferous carbon) in the Witwatersrand (Liebenberg, 1955) and has recently been found in a form suggesting exsolution from colloidal hydrocarbon aggregates in the skarn deposit at the Richardson Mine, Eldorado, Ontario (Boyle and Steacy, 1973). The source of the hydrocarbons, whose residuals after extensive polymerization are amorphous carbon and graphite in many black quartz veins and thucholite aggregates in the Witwatersrand and Richardson Mine, is conjectural as already discussed above. Bituminous materials and polymerized hydrocarbons are frequent constituents of inclusions in quartz and other minerals in many veins (not generally gold bearing) and pegmatites of practically all ages. In the writer's experience, most of these deposits occur in or near sedimentary rocks, and the hydrocarbons may have come from these rocks by means of metamorphic secretion processes. Some investigators think the hydrocarbons, including aromatic, olefinic, paraffin, polar and other phases, are biogenic; others consider them to be abiogenic. We are really dealing here with the origin of petroliferous substances and the nature of early life, subjects beyond the scope of this work. A recent interesting paper discussing the origin of a variety of organic spheres and particles in quartz is that by Mueller (1971).

While amorphous carbon and graphite are common colouring agents for goldbearing quartz, hydrocarbons appear to be relatively rare. None was observed in samples examined by the writer by UV and other methods. Personal communications, however, suggest that quartz and other minerals from deposits younger than Precambrian age may contain hydrocarbons, but at the time of writing no samples were available for testing. Others examining gold deposits should test the constituent minerals for hydrocarbons, because these substances may be important academically in explaining the transport and precipitation of gold in its various deposits. Recently Baskakova (1970) has observed bituminous substances, which on analysis proved to be hydrocarbons and humic acids, in the gold-quartz veins of the Kyzyl-Kum desert, U.S.S.R. These deposits are mainly of Paleozoic age, and the bituminous matter probably came from the organic (carbonaceous) matter in the host carbonate rocks and shales. According to Baskakova the bituminous matter acted as a precipitant of the gold and sulphides. From the descriptions it appears more probable that some of the gold and probably

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[22] It is of interest to note that Horwood (1917) examined the problem of the colour of the quartz in the Witwatersrand by chemical and heating tests but did not come to a specific conclusion about the origin of the black colour of some of the pebbles. He figured numerous fine examples of black-edged pebbles that are obviously due to radioactive darkening a process that was not understood in Horwood's time. Horwood's research, however, is an excellent example of reporting the exact facts so that those who follow similar investigations can utilize the facts in the light of new knowledge.

part of the sulphur were carried into the deposits by the bituminous substances.

The nature of the carbon in quartz veins and other deposits appears to vary with the grade of metamorphism of the rocks in which the deposits occur. In the greenschist and sericite facies the carbon is invariably amorphous; with increasing metamorphism the carbon becomes more organized in three dimensions and is commonly graphite in the amphibolite and higher grade facies.

Black and grey quartz coloured by tourmaline or finely disseminated sulphides is common in quartz veins of all ages. No age differences with respect to abundance of these types of quartz have been noted by the writer.

Amethyst quartz is said to owe its colour to electronic processes (colour centres) based on impurity atoms or ions such as iron, manganese, titanium, nickel, etc. The exact type and concentration of these atoms and ions in the lattice of the mineral has not yet been satisfactorily characterized, but some progress has been made (Frondel, 1962; Dennen and Puckett, 1972). Amethyst is uncommon in gold veins in Precambrian rocks in the writer's experience. If present, it is of restricted or local occurrence in the veins and is generally not auriferous.

In younger deposits, especially those of Tertiary age, amethyst is common in some gold belts. The Veta Madre (Tertiary) of the Guanajuato region in Mexico is noted for its pale coloured amethyst, as are also a number of the Tertiary gold-bearing polymetallic veins in the Banská Štiavnica region of Czechoslovakia and the Paleozoic veins of the Berezovsk (Ural) area of U.S.S.R. (Avdonin and Vertushkov, 1955).

Rose quartz is exceedingly rare in gold deposits despite its common occurrence in pegmatites. Only minor amounts of rose quartz have been observed in the thousands of gold veins seen by the writer and even that present is of exceedingly poor quality and probably would not be considered rose quartz by fanciers of this beautiful mineral. At Yellowknife a variety of flesh coloured quartz is developed in some ladder and ramifying veins. This quartz and accompanying carbonates are late; in places both minerals carry phenomenal quantities of native gold with freibergite (tetrahedrite), chalcopyrite, bournonite and other sulphosalts.

Quartz, highly stained and impregnated by hematite, occurs in a number of gold-bearing polymetallic deposits in various parts of the world. It is common in the Tertiary Banská Štiavnica district of Czechoslovakia and is called 'Cinopel' by the Czech mining geologists. Greenish quartz (not prase), coloured mainly by disseminated patches and wisps of chlorite and other greenish silicates such as fuchsite, is especially common in gold-bearing deposits in greenstones (metavolcanic basic rocks). Golden (yellow) quartz is a feature of certain Tertiary deposits, the colour being due to extremely finely divided gold dispersed throughout the crystals and grains of the mineral.

Ribbon quartz and book structure (parallel quartz sheets sandwiched between slabs of wall rock) are common features of gold-quartz deposits throughout the world being particularly abundant in Precambrian deposits and less frequent in those of Paleozoic and Mesozoic age. They are not common in Tertiary deposits. There are numerous theories concerning the origin of these types of quartz, all discussed by McKinstry and Ohle (1949), Chace (1949), Stillwell (1950, 1953*b*) and Boyle (1961*a*). Most concern accretion and replacement processes or combinations of these. Farmin (1941), however, postulated that vein deposition through inflation of partings in the country rock by an injected, quasi-magmatic fluid was the probable *modus operandi.* He thought the ribbon structure was due to inclusions of parallel septa of country rock and of schistose elongation of more angular inclusions during strike faulting. Further discussion of the origin of ribbon quartz is given in the last section of this chapter dealing with the origin of epigenetic gold deposits.

Exhaustive studies of the microscopic character of gold-bearing quartz have been carried out at the University of Toronto mainly under the supervision of Professor F. G. Smith in connection with geothermal and other related research. The literature is voluminous and cannot be summarized in any satisfactory manner here. The reader is, however, referred to the following publications where summaries and bibliographies are given: Adams (1920), White (1943), Smith (1953) and Boyle (1954, 1961*a*).

At Yellowknife the microscopic description of the gold-bearing and barren quartz is typical of that seen in deposits in rocks of practically all ages in Canada. Elsewhere in the world there are some minor differences that are notable and are referred to later. Quartz deposits at Yellowknife are many and varied (Boyle, 1961*a*) (Figs. 17 and 18). Briefly they comprise, the oldest first:

Greenstone belt

1. *Early barren quartz-filled fractures ('bull quartz' with small amounts of feldspar and pyrite (Pl. 1):* These are cut and offset by shear zones and faults containing gold-bearing quartz.

The quartz lenses in the early fractures rarely exceed 25 ft in length and depth, and a few inches in width. They occur principally in the greenstones, but a few are present in the granitic rocks flanking the greenstone belt. The contacts of the lenses with the host rock are knife-sharp in nearly all localities, but some lenses exhibit a few wisps of unreplaced greenish chlorite adjacent to the slightly chloritized wall rock. The quartz in most lenses is coarse grained, but in some it is medium grained with a sugary texture. The colour is usually milky white, and the lustre is vitreous. Most specimens are brittle and break with an uneven splintery fracture.

Thin sections of the early quartz contain coarse- to medium-sized grains that exhibit a moderate degree of undulose extinction and are cut by small ramifying patches of clear quartz grains possessing sharp extinction. Liquid inclusions are present in most of the larger grains and include two types – two-phase inclusions consisting of a large bubble and a liquid, and three-phase inclusions consisting of a large bubble, a liquid and microscopic crystals. Some inclusions are randomly distributed throughout the grains and may be primary. Others mark rotated parts of the quartz grains, not in optical continuity with other parts of the same grain and are probably of secondary origin. Still other inclusions are randomly distributed along variously oriented planes which form a reticulating pattern. These planes of inclusions cut across grain boundaries and must, therefore, be secondary. All quartz grains contain unidentifiable microscopic acicular crystals and other solid inclusions.

Plate 1.
Early quartz-filled fracture, Yellowknife Greenstone Belt, Yellowknife, Northwest Territories.

2. *Gold-bearing quartz lenses and veins in shear zones and fractures:* The quartz in these bodies is mainly massive (Pl. 2) or ribboned (Pl. 3). Some exhibit vague comb structure (Pl. 4). Two or more ages are frequently present. In some veins the oldest quartz is black or grey, the younger is invariably white or milky (Pl. 5). Reversals of this sequence are notable in a few veins (Pl. 6). Mottled varieties (Pl. 7) are the result of brecciation of black and grey quartz and infilling by white and milky quartz, followed by widescale recrystallization of the mass. All ages of quartz contain carbonates, pyrite, arsenopyrite, stibnite, various sulphosalts, pyrrhotite, sphalerite, chalcopyrite, galena, scheelite, gold and aurostibite.

The macroscopic features of the quartz in the composite lenses (Pl. 2) is essentially the same in all occurrences. The colour of the quartz varies from dark to light grey to white depending upon the amount of graphite or carbon, grey sulphides, sulphosalts and liquid inclusions present. In parts of the Campbell System a light flesh-coloured variety occurs in some lenses. Ribbon structues are ubiquitous in all lenses, but much massive quartz occurs locally. Vugs, containing comb quartz, are rare. Most of the quartz has a vitreous, slightly schistose appearance and is brittle; some varieties, however, have a pronounced cherty appearance, are tough and break with a conchoidal fracture.

The microscopic features of the quartz in the composite lenses are similar in all occurrences. In thin sections the quartz appears as medium-sized grains and microcrystalline grains. The medium-sized grains generally show extreme undulose extinction and are crowded with innumerable solid and liquid inclusions. These features, as well as the presence of abundant

Plate 2.
Typical composite gold-quartz lenses composed essentially of massive quartz, Campbell shear zone system, Negus Mine, Yellowknife, Northwest Territories.

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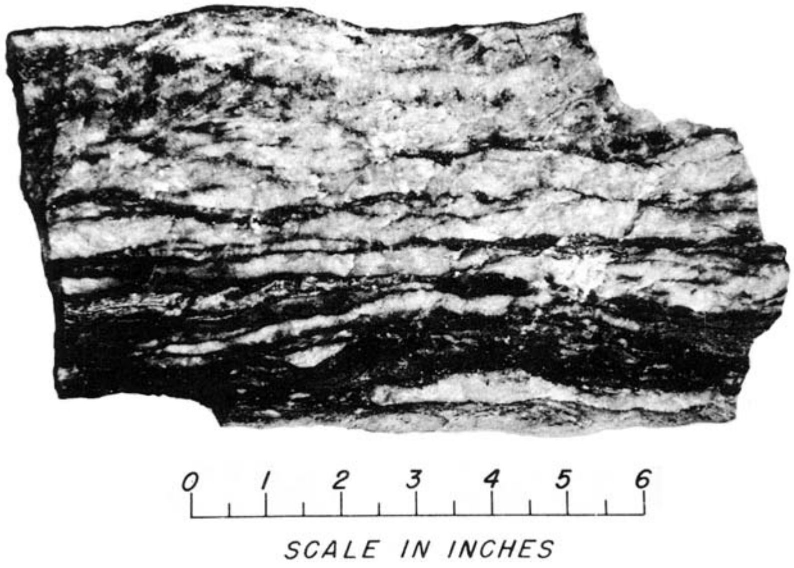

Plate 3.

Ribbon quartz, Campbell shear zone system, Negus Mine, Yellowknife, Northwest Territories.

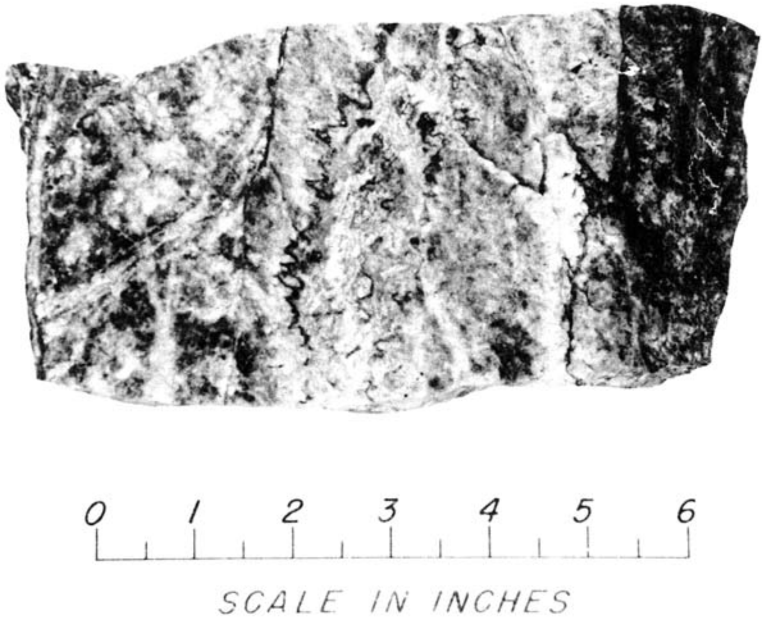

Plate 4.

Grey quartz exhibiting comb structure, Negus-Rycon shear zone system, Yellowknife, Northwest Territories.

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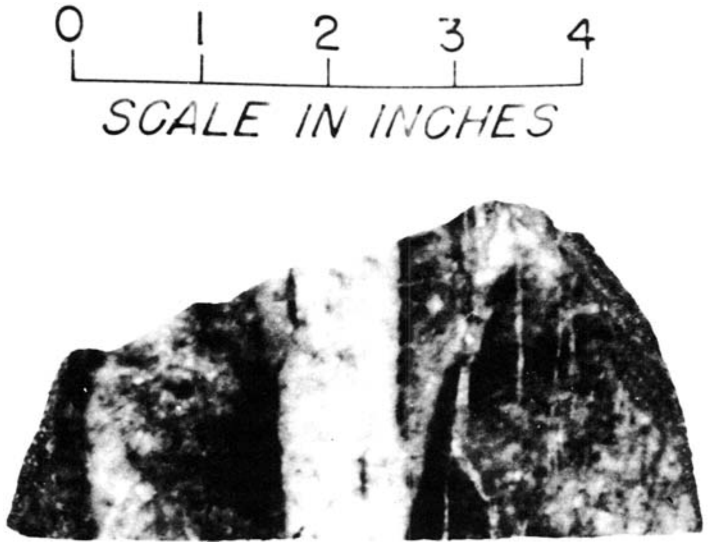

Plate 5.

Early black quartz cut by younger generation of white quartz, Negus-Rycon shear zone system, Yellowknife, Northwest Territories.

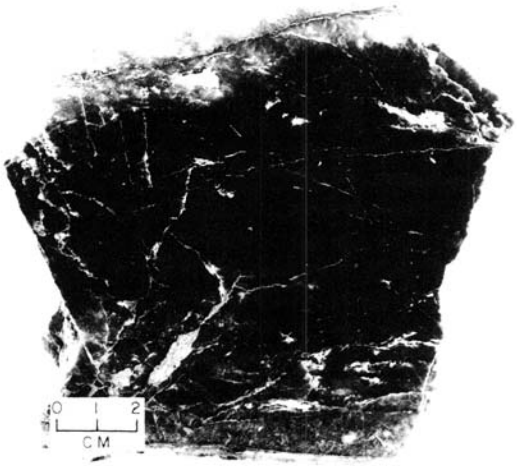

Plate 6.

Late generation of black quartz flanked by grey quartz, Negus-Rycon shear zone system, Yellowknife, Northwest Territories.

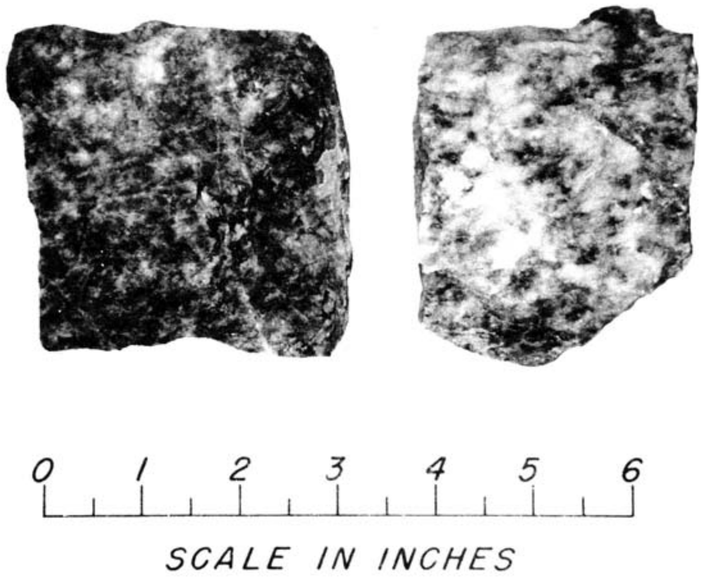

Plate 7.

Mottled varieties of quartz, Negus-Rycon shear zone system, Yellowknife, Northwest Territories.

microcrystalline clear quartz, are indicative of gold-bearing quartz and serve to differentiate it from the quartz in granites, pegmatites and late faults. The microcrystalline quartz is clear with sharp extinction and contains only a few liquid and solid inclusions. It marks the grain boundaries of medium-grained quartz and forms irregular patches, seams and phantom veinlets throughout this quartz.

In most lenses medium-grained quartz predominates and generally constitutes some 70 per cent of the quartz present; in other lenses the microcrystalline type may predominate and a cherty quartz is developed.

The liquid inclusions generally have two phases, liquid and gas. They are distributed at random through the quartz grains, along planes restricted to individual grains, or along diffuse planes transecting the boundaries of several grains. In some medium-sized quartz grains, beady lines of inclusions mark parts of the crystals slightly rotated out of optical continuity. Solid inclusions are distributed throughout the medium-sized grains and the fine-grained clear patches and veinlets. In most cases, where the identity of the solid inclusions can be established, they are fragments of carbonate, sericite, apatite, rutile or tourmaline. Some of these inclusions may be unreplaced fragments of the wall-rock minerals, and others may have crystallized with the quartz.

Some shear zones in the Negus-Rycon System and in the Shaft zone of the Con System contain gold-bearing quartz veins, which exhibit features somewhat different from the lenses just described. In these shear zones the veins are flanked by a slight schistose, dense dykelike alteration zone. The quartz veins are markedly vuggy and vague comb structures are common (Pl. 4). The vuggy parts are filled with carbonate minerals, and some contain sulphosalts.

Some shear zones of the Negus-Rycon System contain two ages of early quartz. The first is black to grey in colour and is partly replaced and veined by milky quartz (Pl. 5). In some veins, black and grey quartz abuts the vein walls, and the milky quartz occupies a medial position; in other veins the reverse is true (Pl. 6). Many veins contain a mottled variety of quartz that consists of small nuclei of black and grey quartz in a matrix of white quartz (Pl. 7).

Thin sections of the quartz from the above two shear-zone systems show many of the quartz grains to be euhedral or subhedral in outline. Growth lines, marked by primary liquid inclusions, are abundant, and secondary inclusions along planes cutting grain boundaries are common. Microscopic trains of carbon particles occur in the black and grey quartz and are primarily responsible for its colour.

3. *Quartz-filled fractures that form ladder veins and ramifying patterns in the shear zones:* These veins (Pls. 8 and 9) cut the auriferous lenses, veins and schist zones and are essentially barren in an ore sense. Most contain carbonates (mainly calcite or dolomite), and some contain small amounts of pyrite, arsenopyrite, chalcopyrite, sphalerite, galena, tetrahedrite, other sulphosalts and gold.

The macroscopic features of this age of quartz differ from those of the early gold-bearing quartz. In most occurrences the quartz is coarse grained, exhibits euhedral to subhedral crystals and is vuggy. Quartz in the stringers that have a strong development of bulbous masses is fine grained, slightly schistose, and may be cherty locally. The vuggy parts of the stringers and lenses contain calcite and ankerite and locally tetrahedrite, chalcopyrite and some gold. Lenses, which exhibit replacement features, include abundant unreplaced fragments of sericite schist containing pyrite and arsenopyrite, chlorite schist and early quartz. The contacts of the quartz with the various types of schists and early quartz is generally sharp and alteration zones are absent. The colour of the quartz ranges from white to faintly flesh coloured. Some irregular crosscutting stringers in the Giant System contain black or grey quartz and calcite due to dispersed microscopic particles of carbon in the two minerals.

Microscopic examination of this age of quartz shows

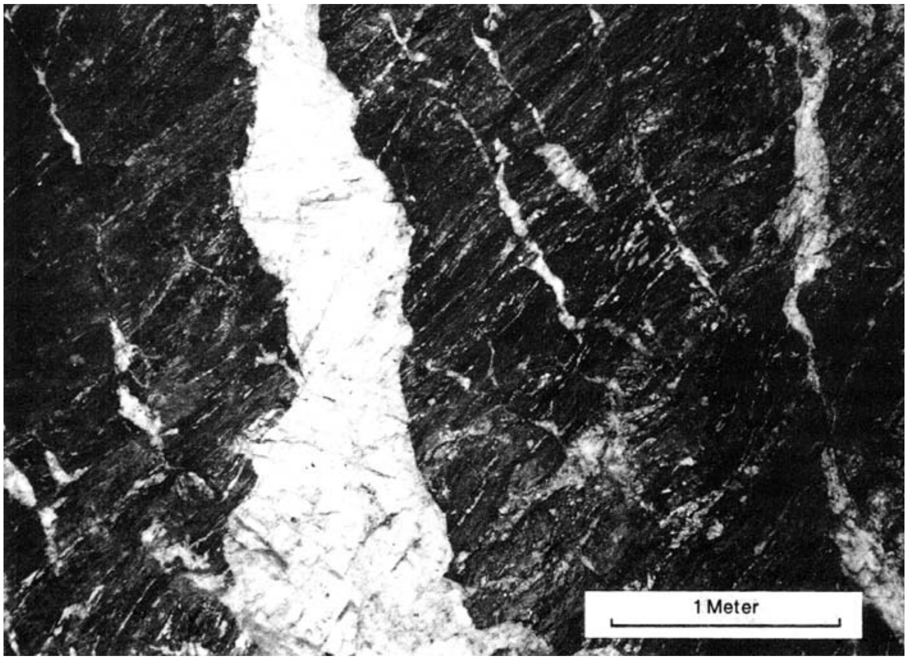

Plate 8.

Late quartz veins and lenses cutting silicified and mineralized schist zone, Con shear zone system, Yellowknife, Northwest Territories.

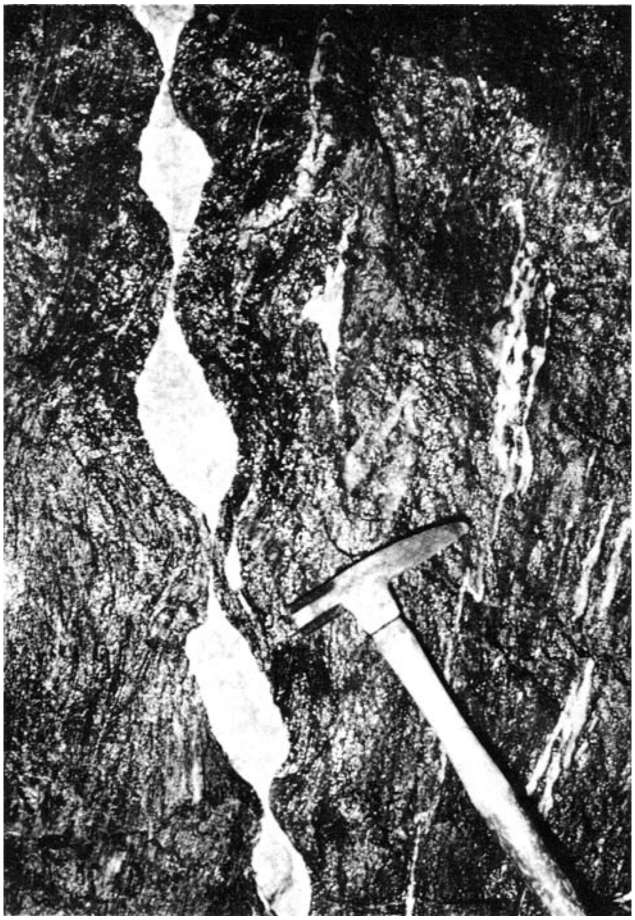

Plate 9.
Late quartz-carbonate veins arranged in en echelon bulbous masses, Campbell shear zone system, Negus Mine, Yellowknife, Northwest Territories.

many of the grains to be relatively clear and to have a general subhedral to euhedral habit with growth planes marked by primary liquid inclusions. In addition, randomly oriented solid and liquid inclusions, and a few planes of secondary liquid inclusions, are generally present. The quartz in the bulbous masses is commonly highly crushed, brecciated and recrystallized with a development of much fine-grained clear quartz. Grains, which escaped mylonitization, exhibit extreme anomalous extinction. These facts suggest that the bulbous masses are the result of structural contortion of the veins and stringers with consequent recrystallization in place.

Sedimentary area (Yellowknife Supergroup sediments)

Three types of quartz deposits occur in these rocks. Their age relationships could not be established with certainty when the first investigation was carried out in 1950. More recent detailed investigations in 1970 suggest that the deposits are probably contemporaneous, or nearly so, their differences being due only to the metamorphic facies in which they occur. The types of quartz deposits are:

1. *Quartz-bearing pegmatities in granite (Prosperous Lake granite) and adjacent quartz-mica schist and hornfels:* These carry no gold; assays of many samples all yield gold in amounts less than 0.01 ppm. The quartz is colourless to white or milky. Some varieties, mainly in the granitic areas have a faintly smoky colour.

Thin sections of the pegmatitic quartz show it to be composed of interlocked, clear, coarse grains with a general sharp extinction. Large irregular liquid inclusions with stationary bubbles and negative crystals with similar bubbles are a distinctive feature of the quartz. Solid inclusions include apatite, tourmaline, garnet, zircon and mica. Tourmaline tends to favour the quartz parts of the pegmatites, and garnets have a slight tendency to the same habit.

2. *Vitreous quartz of mainly one age in lenses and veins in greywacke, argillite, slate and their metamorphic equivalent, the knotted quartz mica schists:* The quartz lenses in the inner zone of the knotted quartz-mica schist aureole adjacent to the Prosperous Lake granite are regular with short and narrow dimensions; others are highly contorted ptygmatic veins (Pl. 10). The quartz in the lenses and veins has sharp contacts with the enclosing schist and hornfels, and fragments of wall rock in the lenses and veins are rare. Alteration haloes about the veins and lenses are not pronounced. Many lenses contain crystals and chalky weathering feldspar, and tourmaline, andalusite, muscovite and garnet are common in lenses cutting schists that contain an abundance of these minerals. Thin sections taken from samples of these quartz veins display a groundmass of clear grains possessing undulose extinction and containing a few liquid and solid inclusions. Patches and irregular veinlets of microcrystalline quartz intersect the groundmass of clear grains in most sections.

Most of these quartz veins are barren and contain no more than 0.1 ppm Au and 0.5 ppm Ag in most occurrences. On Outpost Island in Great Slave Lake, however, similar quartz bodies are auriferous (Lord, 1951). Some of the veins and lenses in the Yelllowknife area resemble pegmatites in the quartz-mica schists and appear to be a transition phase between quartz veins and pegmatites. Despite extensive investigations they have not been observed to grade from one to the other along strike or dip. The quartz is generally glassy ranging in colour from dense black, through grey, to bluish grey, to colourless, white or milky.

The features of the quartz deposits in the relatively unaltered sediments are clearly shown in the lenses at the Burwash prospect. Here, the quartz occurs in short narrow lenses having extremely sharp contacts with the slightly altered. wall rocks. Ribbon structures are rare, but a few fragments of schist and chlorite occur in the quartz. The colour of the quartz in most lenses is bluish black as a result of disseminated graphite; locally a mottled variety composed of diffuse areas of white to light grey quartz in dark grey to black quartz is present. A few grains of albite may occur intimately intergrown with the quartz grains, and a few veinlets of albite and carbonate may transect the massive quartz in places. Sulphides and native gold are sporadic in their occurrence.

Thin sections of the bluish quartz show that it is composed of a groundmass of medium-sized grains exhibiting anomalous blocky extinction features and containing numerous ovoid spots of graphite. Other solid and liquid inclusions, arranged at random and along reticulating planes, are common.

Plate 10.

Ptygmatic quartz veins in quartz-mica schist, Prosperous Lake, Northwest Territories.

The groundmass of medium-sized grains is cut and intersected by ramifying veinlets and patches of fine-grained clear quartz with sharp extinction and contains a few specks of graphite and other solid inclusions.

3. *Grey and white or milky quartz of two ages in veins and lenses mineralized with sulphides and gold:* These occur in fractures, faults, ruptured axes of folds, in contorted zones and as saddle reefs in greywackes, quartzites, argillites, slates, and their metamorphic equivalents, the quartz-mica schists. The early variety of quartz is black, grey or bluish grey, coloured by disseminated amorphous carbon in the argillites, greywackes, slates, etc. and by graphite in the quartz-mica schists. This quartz is cut or impregnated by a later white or milky variety (Pl. 11). Both varieties contain pyrite, sphalerite, galena, chalcopyrite, arsenopyrite, native copper, gold, tourmaline and minor scheelite.

Most of the quartz lenses and veins, which contain two ages of quartz and are mineralized with sulphides and gold, are localized in the outer part of the knotted quartz-mica schist aureole. Typical examples are the Ptarmigan series of lenses that occur in faults cutting quartz-mica schist (Fig. 37). The lenses are commonly arranged in an *en echelon* manner and may average 200 ft in length and 10 ft or more in width. In most places the lenses have sharp contacts with the slightly altered quartz-mica schist, and only a few inclusions of schist occur in the quartz near the walls. Ribbon structures are rare. Vugs containing euhedral quartz crystals, carbonate, pyrite, sphalerite, galena and gold are common; seams and patches of tourmaline, albite and carbonate are present in some part of the veins.

The Ptarmigan quartz lenses contain two ages of quartz. The first is mottled bluish grey, medium-grained quartz and makes up most of the lenses; the second is a limpid white, medium-grained quartz that cuts across and may replace the first age (Pl. 11).

Thin sections show the first age to be composed of medium-sized interlocked grains with a moderate degree of wavy extinction. The most characteristic inclusions in the grains are ovoid spots of graphite, which are mainly responsible for the grey colour of the quartz. Small numbers of random and planar liquid inclusions are generally present, together with some chlorite and sericite and a few unidentified acicular needles. The medium-sized grains are intersected by numerous veinlets and patches of fine-grained, clear quartz

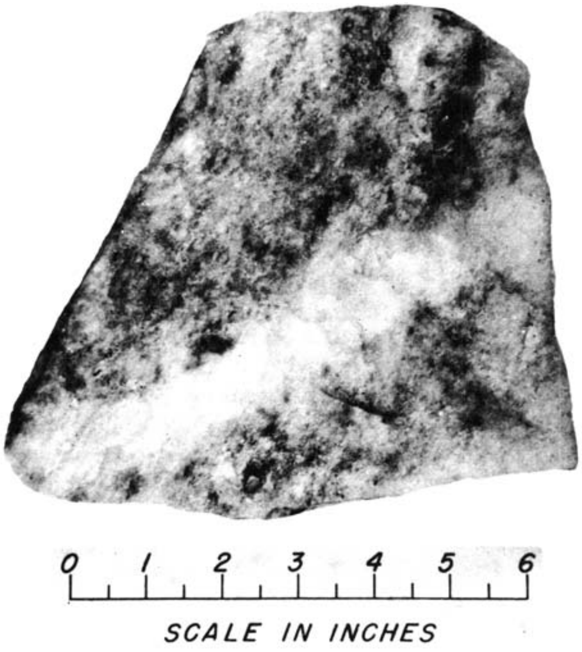

Plate 11.

Early grey quartz cut by later white quartz, Ptarmigan Mine, Yellowknife, Northwest Territories.

exhibiting sharp extinction and containing a few solid and liquid inclusions. Thin sections of the second age of quartz show that it is composed of an interlocked mass of relatively clear, medium-sized grains, which contain a few spots of graphite and some random liquid and solid inclusions.

Extensive faults cutting greenstone, sedimentary and granitic areas

Great faults extending for many tens of miles cut the greenstone, sedimentary and granitic rocks of Yellowknife and adjacent areas. Locally these faults contain enormous quartz veins and stockworks, locally called 'giant quartz veins'. As far as is known these bodies are essentially barren of gold, analyses revealing no more than 0.025 ppm Au and < 0.4 ppm Ag. In places they contain pyrite and chalcopyrite. Two general types of quartz bodies are present – relatively small quartz lenses and the 'giant quartz veins' noted above.

The smaller lenses consist of a groundmass of highly intergrown quartz crystals surrounding breccia fragments; in others the lenses are made up principally of prismatic comb quartz, which lines cavities in the faults. The quartz is commonly colourless or milky. In some lenses amethyst may occur.

In thin sections the intergrown quartz crystals of the small lenses exhibit a general euhedral to subhedral character, and relatively little mylonitization is present. Fracturing is common, however, and in most thin sections late carbonates and chlorite may fill the breaks. Primary liquid inclusions mark growth lines, and in some sections abundant secondary planar inclusions are present. Solid inclusions are abundant and include mica, chlorite and carbonates.

The comb quartz is composed of small to large prisms with milky bases and clear tips. In thin sections these crystals exhibit excellent growth zones, and all are crowded with large, two- and three-phase liquid inclusions. The surface of the crystals is etched in places, and solid inclusions such as chlorite, carbonates and sericite are present within growth zones and along growth planes. Many of the prismatic quartz crystals are fractured and healed by fine-grained clear quartz containing pyrite, chalcopyrite, chlorite and small amounts of carbonates.

The 'giant quartz veins' are remarkable structures and have been found in many of the late faults in the Northwest Territories. An excellent description of the structural characteristics and texture of these veins is given by Furnival (1935).

The 'giant quartz vein' at the junction of the West Bay and Akaitcho faults is a large stockwork that varies from 100 to 300 ft in width, and though not continuous, extends for nearly 2 mi along the West Bay Fault (Fig. 17).

The structure of the stockwork is complex and consists of several large lenses of massive white quartz intersected by innumerable veinlets of subhedral milky quartz containing many druses and elongated cavities lined with clear quartz prisms. Hematite is ubiquitous in the druses and cavities and forms a reticulating series of seams and veinlets throughout the massive quartz lenses and adjacent wall rocks.

Three distinct ages of quartz, each preceded by a period of fracturing, are developed in the stockwork. The first age of quartz is represented by large irregular lenses of massive white quartz, which developed after the initial fracturing and brecciation that formed the West Bay Fault. Only small amounts of hematite are associated with this age. The lenses appear to have been emplaced partly by replacement of the highly brecciated fault zone because most lenses contain abundant fragments of partly replaced breccia fragments. Thin sections of this age of quartz show it to contain medium- to small-sized anhedral interlocked grains enclosing some random liquid inclusions and numerous solid inclusions. Most grains exhibit anomalous extinction, and mylonitization of the larger grains is widespread.

After the massive lenses were formed, a second period of fracturing took place. This brecciated the early quartz lenses and adjacent wall rocks, especially the granodiorite, for distances up to 300 ft outward from the fault zone. Following this stage of brecciation quartz and hematite were deposited. The quartz is fine grained and anhedral; some is microcrystalline forming a red or black jasper as a result of occluded hematite.

The third stage of brecciation is local in places, but in others it extends outward from the fault plane for 100 ft or more. The fractures formed during this period are filled with comb quartz, and many druses and elongated cavities occur. In some cavities small amounts of red hematite encrust the small quartz prisms. In thin sections the third age of quartz exhibits marked euhedral characteristics: growth lines marked by liquid inclusions and a few solid inclusions are a common feature.

The chemical composition of 'pure' samples of all the quartz types at Yellowknife described above are given in the writer's original work (Boyle, 1961*a*) and need not be repeated here. The general conclusions reached by the writer are as follows:

> The contents of minor elements are extremely erratic and generally have a wide range from sample to sample in the same setting. It is very doubtful if the contents of minor elements reflect anything but the degree of contamination by sericite, sulphides, carbonates, etc. It is nearly impossible to remove these extraneous minerals by leaching and other treatment, because they are so intimately intergrown with the quartz. It follows, therefore, that contamination by the elements present in intergrown minerals masks any systematic variations in the substitution of elements in the quartz lattice or any variation in the elements in the salts present in the crystal cavities.

The problem of differentiating ore-bearing from barren quartz by the eye or microscope, is likewise, extremely difficult. At Yellowknife most of the ore-bearing quartz in the greenstone belt is intensely crushed and in part recrystallized, and there are often several generations of quartz probably in part representing remobilized silica from the confines of the veins and lenses. This feature has also been emphasized by Petrovskaya (1970) for deposits in U.S.S.R. Multiple generations or redeposition of quartz is less noticeable in the deposits in the sedimentary area. Ore quartz is invariably crowded with liquid and solid inclusions, and this is probably a good microscopic criteria for the differentiation of ore and barren quartz. Much of the gold in the quartz is late, occupying small fractures, crevices and seams in the quartz and other minerals. Where comb quartz is present the native gold and other gold minerals occupy interstices between the separate layers of crustified quartz. These features may be repeated, but invariably any one age of quartz is generally followed by a late deposition of gold and gold minerals.

The quartz in other gold deposits of Precambrian and younger rocks exhibit features similar to those described for Yellowknife, and much of the native gold, tellurides and other gold-bearing minerals are invariably late. Some Tertiary deposits contain abundant rhythmically banded chalcedonic quartz (Pls. 12 and 13) and in this respect are somewhat different from the older deposits. The relationships of gold minerals to this quartz are, however, usually similar to those existing in older deposits.

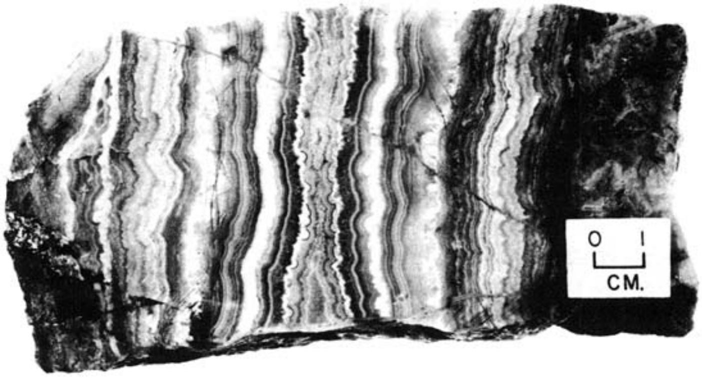

Plate 12.
Rhythmically banded chalcedony, Madjarovo veins, Eastern Rhodope Mountains, Bulgaria.

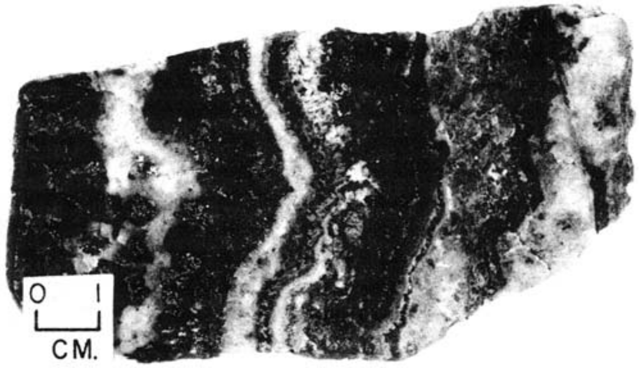

Plate 13.
Rhythmically banded quartz, chalcedony, carbonates and sulphides (galena, sphalerite, chacopyrite, pyrite), Tui Mine, Te Aroha, New Zealand.

The detailed relationship of gold to quartz in auriferous deposits is of considerable interest from the viewpoint not only of origin but also metallurgical practice in winning the precious metal from its ores. Mawdsley (1938), White (1943), Ebbutt (1948), Urashima (1956), Petrovskaya (1970, 1973) and Petrovskaya *et al.* (1971*b*) have dealt with some aspects of this subject. The summary to follow complements their work and extends the data to all types of deposits.

Gold-bearing pegmatites. In these deposits the relationships are essentially the same as those noted below for gold-quartz veins and silicified zones. The gold is mainly closely associated with sulphides or occurs in the free state in late fractures in the quartz and other minerals.

Skarn deposits. Gold occurs in these bodies in four forms. (1) In or closely associated with pyrite, arsenopyrite, tetrahedrite and other sulphides and sulphosalts as a lattice constituent or in microscopic form: The microscopic gold is usually distributed at random in the sulphides and sulphosalts. Paragenetically, it is usually a late mineral often occurring in minute fractures and seams. (2) In native arsenic as in the Bau deposits Sarawak: The gold is a lattice constituent and also appears in microscopic particles. (3) In tellurides: No good relationships can usually be established. Probably most are paragenetically late minerals. (4) As native gold: The metal is usually in contact with quartz, Ca-Mg-Fe-Mn–silicates, carbonates, etc.; the native gold is late, occupying tiny fractures and seams in quartz and these other minerals.

Gold-quartz veins, lodes and silicified zones. Gold occurs in a number of ways in these deposits. (1) In or closely associated with pyrite, pyrrhotite and arsenopyrite as a lattice constituent or in microscopic form (*see also* the section on gold in other minerals in Chapter II): The microscopic gold is usually distributed at random in the sulphides. Paragenetically, the gold is usually a late mineral often occurring in minute fractures or seams or rimming the sulphides. (2) In sulphosalts, mainly tetrahedrite or tennantite; in stibnite; in realgar; and in other sulphides and sulphosalts such as galena, sphalerite, chalcopyrite, boulangerite, jamesonite and enargite: The gold is a lattice constituent of some of these minerals; it also appears in microscopic form in a random fashion and in tiny fractures and seams in these minerals. (3) As native gold in contact with quartz and other gangue minerals: The gold is paragenetically late occurring in small faults, fractures, crushed areas, slips, chloritic and sericitic seams and small vuggy parts of the quartz (Pl. 14). In young deposits (Tertiary) the gold may be moulded around quartz crystals or occur in bands between successive combs or layers of quartz. (4) As aurostibite: Most of the aurostibite in gold deposits occurs in close proximity to gold and forms haloes and coatings about the gold particles or is present in narrow seams in the gold. It is also associated with gold as small diffuse aggregates scattered along the contacts of arsenopyrite, stibnite and sulphosalts. In most polished sections it appears to be later than the gold, but good age relationships are uncommon. Aurostbitie is usually restricted in its occurrence to deposits containing concentrations of antimony minerals and gold. (5) As tellurides: There is probably no gold deposit without gold-silver tellurides, although they may be present only in trace amounts. In nearly all deposits the gold tellurides accompany native gold and are late minerals in the paragenetic sequence occurring in fractures, slips and crushed zones in the quartz and other gangue minerals. Where crustification is prominent the gold and tellurides are invariably late following the deposition of quartz, carbonates, etc. In individual veins there may be several generations of crustified minerals, including native gold and gold tellurides, each superimposed on an earlier generation.

Auriferous polymetallic and massive sulphide deposits. In polymetallic deposits the relationships are essentially the same as those noted above for gold-quartz veins and silicified zones. In many of these deposits much gold is intimately associated with the sulphide and sulphosalt minerals being present either as lattice constituents or as microscopic particles. In the

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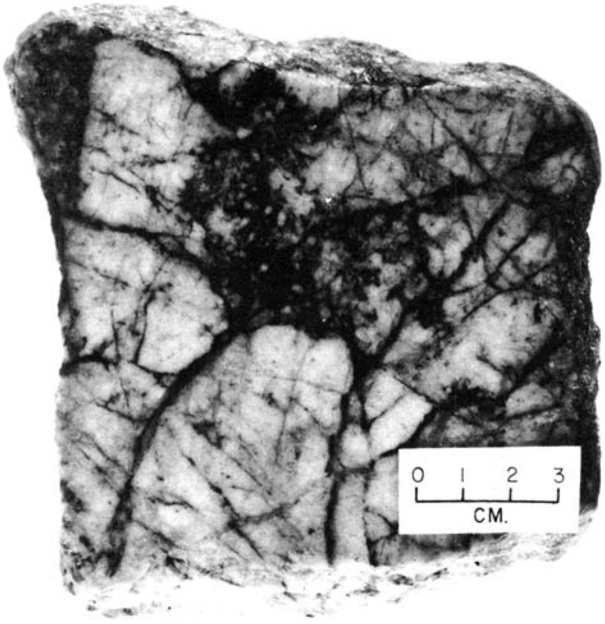

Plate 14.
Native gold associated with late generations of stibnite and sulphosalts (tetrahedrite, bournonite, jamesonite), Negus-Rycon shear zone system, Yellowknife, Northwest Territories.

massive sulphide deposits the distribution of the gold is varied, but invariably the bulk of the element is late in the paragenetic sequence. There is also a minor generation of gold which accompanies each stage of the sulphides and occurs in them as microscopic particles or in lattice sites. The classic account of the distribution of gold in massive sulphide bodies is that by Price (1934) who studied the rich auriferous Noranda ores. He identified the following main types of gold mineralization in the great massive sulphide bodies: (1) gold and tellurides (especially the former) forming minute veinlets, irregular areas and dots in idiomorphic pyrite crystals; (2) veinlets (predominantly gold) along the borders of pyrite crystals, between the pyrite and the adjacent sulphide; (3) gold-telluride areas replacing pyrrhotite, the free gold particles being surrounded or 'sheathed' by tellurides; (4) gold replacing chalcopyrite; (5) gold and tellurides in veinlets and angular patterns replacing minute chlorite aggregates in the massive sulphides; (6) quartz veinlets carrying gold and tellurides, cutting the earlier sulphides; and (7) type 5 repeated at the contact of highly chloritized syenite porphyry where such material occurs in the midst of a large sulphide mass.

Gold-bearing quartz-pebble conglomerates. An enormous amount of microscopic work has been done on these deposits. Early summaries of research are given by Graton (1930). Later work is described in detail by Liebenberg (1955) in his extensive paper on the Rand. Saager (1969) summarizes the recent research on the Rand in his paper on the relationship of gold and silver, and Feather and Koen (1975) have added further data. Gross (1968) describes the relationships of the gold to other minerals in the Jacobina conglomerates in Brazil, and Bray (1928) and Kitson (1930) give similar data for the Tarkwa conglomerates in Ghana. (*See also* the section on these deposits in a later part of this chapter.)

Detailed descriptions of the varieties of quartz in the quartz-pebble conglomerates are given in a subsequent section dealing with these deposits. Briefly, the quartz occurs in pebbles that are cemented by a matrix consisting of quartz grains, micaceous minerals, pyrite (Pl. 15) or iron oxides (Pl. 16).

Saager (1969) describing the occurrence of gold in the Rand says:

> The gold in the Basal Reef occurs in much the same way as in other ore-horizons of the Witwatersrand Goldfield. It varies

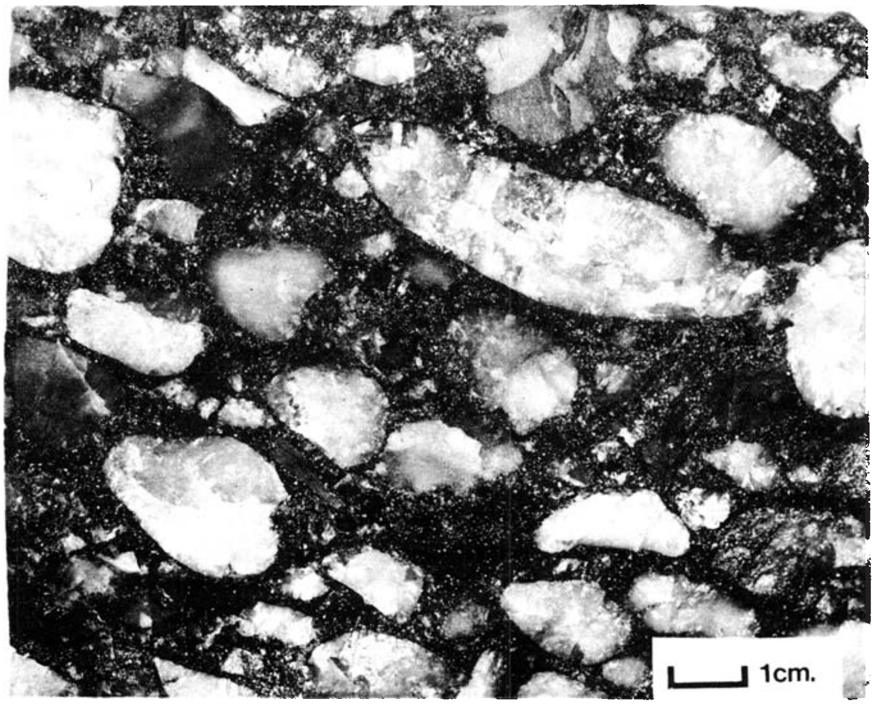

Plate 15.
Auriferous pyritic quartz-pebble conglomerate, Main Reef Leader, Robinson's Deep, Witwatersrand, South Africa.

Contents

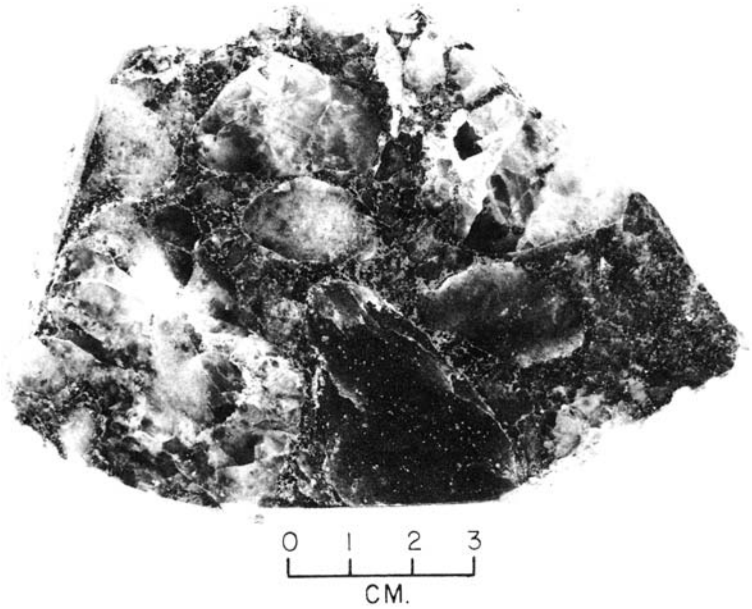

Plate 16.
Auriferous, hematitic quartz-pebble conglomerate, Tarkwa goldfield, Ghana.

> considerably in grain-size from 1 micron to over 1,000 microns, commonly averaging between 5 and 100 microns. Macroscopically visible gold is only very rarely encountered. Usually the gold occurs as irregular, jagged particles among the matrix constituents of the conglomerate and is intimately intergrown with secondary, reconstituted sulfides, or it fills fractures and cavities in earlier formed minerals. Frequently the gold during its reconstitution, has migrated into the marginal areas of porous pyrite grains where it now forms secondary inclusions. Primary inclusions and myrmekitic intergrowths of gold with detrital pyrite and linnaeite have occasionally been observed. Rarely, rounded gold grains are found in the matrix. According to a suggestion by Liebenberg (1955), these possibly represent detrital gold particles which still exhibit the abraded morphology obtained during transportation.
>
> The close relationship between gold and thucholite in many Witwatersrand ores has been known for a long time, suggesting precipitation by the latter on gold taken into solution. The common close association also of uraninite with gold has led Liebenberg (1955) to suggest that the uraninite may have exerted a precipitating effect of gold from solution.
>
> A vast array of incontrovertible macroscopic and microscopic evidence now accumulated from all areas of the Witwatersrand and associated subsidiary basins leaves no room for doubt that the gold is essentially of placer origin. The mode of occurrence of the gold and especially its relationship and association with other minerals clearly indicates subsequent mobilization and redeposition during the metamorphism of the Witwatersrand sediments.

No specific mention is made of quartz in this description, and it should perhaps be noted that occasionally gold is seen in small fractures in the quartz pebbles. There are also quartz veins in the Rand system that seem to receive little attention by the placerists. Graton (1930) refers to these and states that they carry the same minerals as the matrix of the conglomerate, viz. sulphides, sericite, chlorite, carbonates and gold. The gold is a late mineral in these veins.

According to Gross (1968) the bulk of the gold in the Jacobina conglomerates occurs in the sandy matrix. It is usually present as grains varying in size from 0.05 to 0.01 mm. Within individual conglomerate beds the gold increases markedly toward the tops of the beds. This suggested remobilization of (placer) gold to the author, who also points out that occasionally thin plates of gold are found in fractures in the pebbles and in the conglomerate. In some polished sections grains of pyrite occasionally exhibit crystal structure, which in places may embay or surround gold particles. Where ultramafic rocks form sills and steeply dipping dykes in the gold-bearing horizons, concentrations of gold occur near the contacts of these intrusions.

According to Bray (1928), Kitson (1930) and Rozhkov (1967) the matrix of the Tarkwa quartz-pebble conglomerate consists of quartz grains, sericite, chloritoid and much hematite and some magnetite in granular form. The gold is essentially all in the matrix, but some is found around the quartz pebbles and in little fractures in the matrix. Numerous quartz veins also traverse the Tarkwa conglomerate, and these carry pyrite, siderite, hematite and minor amounts of gold, the last a late mineral in the paragenetic sequence.

Summary of features of quartz in auriferous and barren deposits

It is difficult to summarize all of the above features of auriferous and barren quartz, but certain aspects seem to stand out in the writer's opinion.

Quartz deposited, reworked or recrystallized under deep-seated conditions in high grade metamorphic terranes (hypothermal deposits of some geologists) generally occurs in coarse-grained compact aggregates and is usually relatively clear and glassy to subvitreous and milky; some varieties are glassy, dark grey to black due to microinclusions of graphite. Vugs and prismatic crystals are rare; ribbon and book structures are uncommon. Liquid inclusions in the quartz tend to be relatively large but restricted in number. Native gold and gold minerals are invariably late occurring in microfractures or brecciated parts of the quartz.

Quartz precipitated, reworked or recrystallized under conditions of medium depth and medium to low grade metamorphism (mesothermal deposits of some geologists) is generally finer grained than the preceding type of quartz. Ribbon and book structures are especially common, and crude and coarse banding is a feature in some veins and lenses. Vugs and druses are common in some deposits but are usually not abundant. The quartz is usually milky to dull grey to black in colour, the last being due mainly to finely divided forms of carbon (carbonaceous matter). Liquid inclusions are abundant, some varieties of auriferous quartz being crowded with these objects. Liquid inclusions range in size from small to large and are of both primary and secondary derivation. Gold and gold minerals are invariably late occurring in microfractures, phantom veinlets or brecciated parts of the quartz.

Quartz deposited under near surface conditions (epithermal deposits of some geologists) generally in zones of low grade metamorphism (propylitic facies) is commonly fine grained, porcellanic, flinty, dull cherty, chalcedonic, to opaline. Some deposits are characterized by medium- to fine-grained quartz. Vugs are universal and cockade structures common; fine colloform banding is often characteristic, and developments of lamellar and hackly quartz are notable in some deposits. The quartz is clear to milky, only rarely dark grey to black. Liquid inclusions are very small. Gold and gold minerals may occur interbanded with successive generations of quartz, or these minerals may be late, filling small fractures and crushed zones in the quartz. Some varieties of quartz in Tertiary veins are heavily disseminated with microcrystalline gold such as to give the quartz a golden yellow colour.

Microscopically auriferous quartz is often characterized by a great abundance of liquid inclusions of both primary and secondary origin. This feature has been noted and commented on by numerous investigators including particularly Smith *et al.* (1949–1951), Boyle (1954) and Machairas (1970*b*). Machairas noted the presence of gold particles in some of the liquid inclusion cavities and observed that the content of CO_2 in the inclusions in the quartz was greatest in auriferous quartz. Finally he concluded that as a generality the concentrations of fluid inclusions and gold in quartz are proportional.

Despite all these favourable indications there is really no satisfactory way of unequivocally distinguishing barren from auriferous quartz as far as is known to the writer except by assay methods. The practised naked eye can sometimes distinguish quartz that is more 'kindly' to gold mineralization within a specific belt but may fail in other belts. Microscopically, auriferous quartz can sometimes be distinguished from barren quartz by the large degree of cataclasis, strain phenomena, recrystallization, phantom veinlets and secondary liquid inclusions, which characterize gold-bearing quartz in many belts. Chemically it is doubtful if auriferous quartz can be distinguished from barren quartz, although more work should be done on this aspect of the problem. The comment of W. M. Courtis (1890) made after a long study of auriferous quartz is appropriate at this point:

> After several years spent among the gold-mines of California with practical and professional gold-miners, I have come to the conclusion that very few care to risk an opinion on a piece of quartz until some of it has been "horned out." Nevertheless, there is what the miners call a "kindly" appearance, that is more often followed by good results than is a vitreous, water-wet-looking quartz. A dark, resinous quartz seems to be most in favor, but there are so many exceptions that even quartz as "white as a hound's tooth" produces gold in some mines.

Silicates of many types are common in the wall-rock alteration zones and ores of gold deposits of all categories. Most of these are discussed in the section on wall-rock alteration processes and the details can be omitted here. Among the feldspars the most common are *albite, oligoclase* and *adularia*. Much has been written on the association of gold and albite, a few of the principal references including those by Lindgren (1906), Gallagher (1940) and Ward (1958). In some cases there is an association with albite dykes or albitization of the wall rocks of the deposits; in other cases the albite occurs as a minor gangue mineral in quartz veins and silicified zones. Albite and oligoclase as vein minerals are relatively common in Precambrian deposits, diminishing in amount through deposits of Paleozoic, Mesozoic and Tertiary age. They occur most commonly in deposits in the higher grades of metamorphism (epidote amphibolite and amphibolite facies). Gold and gold minerals are generally later than albite and oligoclase in their paragenesis. In some places the gold can be seen along the cleavage planes of the feldspars. More details on the association of gold and albite are given in Chapter V. *Adularia* is usually found in the young (Tertiary) gold deposits mainly as a vein mineral. *Valencianite* is adularia; it occurs in some of the auriferous and argentiferous veins of Mexico and the western United States. Gold and gold minerals are generally later than adularia in their paragenesis.

Of the micaceous minerals in gold deposits the most common are *sericite (muscovite), biotite, talc* and *chlorite. Fuchsite* and *mariposite*, the chromium-bearing varieties of muscovite and phengite respectively, are generally restricted to the wall-rock alteration zones of gold deposits in basic and ultrabasic rocks. Some auriferous porphyries also contain fuchsite. *Chromian muscovite* is a common mineral in some of the auriferous quartz-pebble conglomerate bands at Jacobina in Brazil; also in the Rand quartz-pebble conglomerates. *Paragonite* is relatively rare compared with sericite in the wall-rock alteration zones of gold deposits; it occurs most commonly where there is a high degree of soda metasomatism and is often accompanied by albite. *Roscoelite*, the vanadium mica, occurs in a few of the gold quartz veins of the Mother Lode system in California, at Cripple Creek in Colorado and elsewhere. The mineral seems to occur most abundantly in deposits with basic and ultrabasic host rocks. According to Lindgren (1933) roscoelite is often indicative of rich auriferous shoots. In the Kalgoorlie gold belt of Western Australia *vanadium muscovite* (sericite) is particularly common and is responsible for the colour of the 'green leader'. It is closely associated with nolanite, native gold and tellurides (calaverite, petzite, altaite, melonite, coloradoite) (Nickel, 1977). *Pyrophyllite*, $Al_4(Si_8O_{20})(OH)_4$, is a common mineral in the micaceous matrix of the auriferous quartz-pebble conglomerates of the Witwatersrand. According to Liebenberg (1955) it is the main micaceous silicate in the matrix of some of the deposits. Gold is intimately associated with the various micaceous silicates, including pyrophyllite, replacing them completely or partially in places. Pyrophyllite occurs in the wall-rock alteration zones of certain (usually Tertiary) vein deposits. At Rodalquilar in southeast Spain the mineral occurs in the alteration zones, together with alunite, adjacent to veins with high concentrations of gold (Lodder, 1966). *Chloritoid* is not common in auriferous deposits but occurs in the quartz-pebble conglomerates of the Rand in moderate abundance (Liebenberg, 1955). It is commonly accompanied by chlorite and both minerals may be moulded on and around the grains of pyrite as observed in thin sections.

Serpentine is a common mineral in the alteration zones of auriferous deposits developed in ultrabasic rocks; also in certain skarn deposits. The mineral only rarely occurs in the quartz of gold-quartz deposits. In a few deposits native gold occurs in asbestos veinlets in serpentinized rocks; in some places the metal is present along the cross fibres of the asbestos, one characteristic occurrence being at Jones Creek, Gundagai, New South Wales.

The clay minerals, *kaolinite, montmorillonite*, etc., are common in auriferous deposits, primarily in those of Mesozoic and Tertiary age. They result mainly from endogene alteration of feldspars, feldspathoids and other silicates during wall-rock alteration processes. In some deposits the clay minerals are supergene products of oxidation and weathering processes. Gold is commonly intimately associated with kaolinite and the other clay minerals mainly as a result of adsorption processes. (*See also* the section on gold in natural waters in Chapter II.)

Zeolites, such as *stilbite, chabazite, laumontite* and *natrolite*, are not common minerals in auriferous deposits, but significant occurrences are reported in gold-quartz deposits in the Tertiary andesites, basalts and pyroclastics in New Zealand, Indonesia and Japan. Seiranyan *et al.* (1974) describe the wide distribution of calcic zeolites (laumontite, stilbite) in the auriferous sulphide ores of northern Armenia. These deposits are in volcaniclastic and effusive rocks of basaltic and andesitic composition. The zeolites occur both in the quartz-epidote gangue of the deposits and in veinlets and amygdules in the wall-rock alteration halos.

Amphiboles, pyroxenes, olivine, epidote, garnet, wollastonite, andalusite and *cordierite* are most abundant in auriferous skarn-type deposits, although garnet and andalusite have been noted in some abundance in gold-quartz veins in high grade metamorphic rocks. Hawley (1939) and Lord (1951) mention the presence of minerals such as staurolite, andalusite and corundum in the auriferous quartz bodies of Outpost Island, Great Slave Lake, Northwest Territories. These veins also contain ferberite, scheelite and molybdenite. The gold is later than the andalusite and staurolite, occurring frequently in tiny fractures in the former mineral. In the Kabin Mine in Thailand rich gold shoots occurred in quartz-grossularite veins.

All of the above mentioned minerals are commonly encountered in gold placers.

Nephrite (an amphibole) and *jadeite* (a pyroxene) collectively known as jade are frequently found as boulders and pebbles in certain auriferous stream gravels in Asia and elsewhere. This may partly explain why the Chinese have long associated gold with jade, the two most precious substances known to the early Chinese who worshipped both as immortal. The Chinese word for jade *jü* is employed in metaphor to symbolize nobility, beauty and purity much in the same manner as the English words 'gold' and 'golden'.

Tourmaline is one of the commonest minerals in auriferous deposits of practically all types. In some deposits such as the auriferous quartz-pyrite-tourmaline breccia pipes developed mainly in granitic rocks the borosilicate may be nearly as abundant as quartz. Tourmaline occurs both in the wall-rock alteration zones of gold-quartz deposits and in the quartz, carbonates and other gangue minerals. Gold and gold minerals are generally later than tourmaline in their paragenesis, although in some deposits the native gold often occurs along the elongated crystals of the borosilicate, and it is difficult to determine their respective ages. To some investigators the small amounts of tourmaline in the quartz-pebble conglomerates of the Rand are detrital; to others introduced by hydrothermal activity.

Tourmaline is a common associate of gold in auriferous placers.

Beryl is not commonly found in auriferous deposits, but minor amounts of the mineral may occur in skarn-type deposits and in certain veins carrying tin minerals and topaz. Ol'shevskiy (1973) records the presence of aquamarine in the gold-quartz veins of the Karalveem deposit in western Chukotka.

Some gold placers in granitic terranes contain small amounts of common beryl. In New South Wales emeralds are encountered in some gold washings. This gem is also found in auriferous placers in other gem-bearing parts of the world.

Rhodonite, inesite and *johannsenite* are common manganese silicates in young (Tertiary) gold deposits. In these they appear to be relatively early minerals and are commonly associated with manganese carbonates, especially rhodochrosite, manganiferous calcite and kutnahorite (Mn dolomite). *Bustamite* and a variety of other maganiferous silicates occur in small amounts in certain auriferous skarn deposits and high temperature vein and replacement deposits.

Topaz is relatively rare in gold deposits but occurs as an important alteration and gangue mineral in the Brewer Gold Mine. Chesterfield County, South Carolina (Peyton and Lynch, 1953). There, the topaz content may be as much as 17.5 per cent or more with long core lengths of 5 per cent or more. Topaz also occurs in auriferous deposits marked by tin and tungsten (wolframite) mineralization. It is evidently an early mineral in these deposits and may belong to a stage that is more or less divorced from the auriferous phase of mineralization.

Topaz is a minor constituent of some gold placers.

Sphene occurs only rarely in auriferous deposits and principally in skarn-type deposits. *Allanite*, the rare-earth silicate, is, likewise, uncommon in nearly all types of auriferous deposits. It may occur sporadically in skarn-type deposits and has been noted in certain quartz-pebble conglomerates. *Zircon* may occur in various type of auriferous deposits but only in traces; in the Rand the zircon in the matrix of the bankets is uraniferous. According to Liebenberg (1955) it is of detrital origin. In modern gold placers zircon is an invariable associate of gold.

Silicates, which seem not to have been recorded from auriferous deposits, include *pollucite, feldspathoids* and *spodumene*. In the supergene zone zinc silicate, *calamine*, and the copper silicate, *chrysocolla*, occur in the oxidized zones of some gold deposits containing abundant primary zinc and copper minerals.

Carbonates are ubiquitous minerals in most gold deposits being most abundant in the skarn, vein and polymetallic types and least abundant in the quartz-pebble conglomerates. The most common carbonates in gold deposits are *ankerite, dolomite, calcite, rhodochrosite* and *siderite*. *Magnesite* is mentioned as being present in some gold deposits in the old literature, and *kutnahorite*, the manganiferous dolomite, occurs in certain young (Cretaceous-Tertiary deposits). *Aragonite* does not seem to occur in gold deposits; at least there are no modern references to the presence of this carbonate in gold deposits in the literature, and the writer has not observed it in his investigations. *Strontianite* may occur in some gold-quartz deposits, but it is relatively rare as a gangue mineral. *Fluocarbonates* are rarely present in auriferous deposits, although *bastnaesite* and other similar carbonates apparently occur in the Sulphide Queen Mine at Mountain Pass, San Bernardino County, California. In Precambrian, Paleozoic and Mesozoic deposits, *ankerite, dolomite, calcite* and *siderite* predominate in about that order of abundance. Siderite is, however, uncommon in most gold-quartz deposits, but in some such as those in Proterozoic rocks north of Lake Huron, Ontario it is an important gangue mineral. In these the native gold is invariably later than both the quartz and siderite. Tertiary deposits are often characterized by *manganiferous calcite, rhodochrosite* and in places by *kutnahorite*, which are frequently accompanied by manganese silicates such as rhodonite, inesite and johannsenite.

Gold-quartz veins and silicified deposits, particularly those developed in basic volcanic rocks frequently exhibit two or more ages of carbonate. At Yellowknife, and in other gold-quartz deposits of the Canadian Shield, three ages of carbonate are commonly developed in deposits in the greenstone belts. The oldest, developed mainly in the wall-rock alteration zones, is ankerite with high magnesium and iron contents. The second age, present in crosscutting quartz-carbonate veins and lenses, is ankerite or calcite, characterized by a higher calcium content and lower iron and magnesium contents compared with the oldest carbonate. The youngest carbonate, in late crosscutting slips and small faults, is invariably calcite with low contents of magnesium and iron. In all three stages of carbonate, manganese remains relatively constant, with a slight increase in the youngest age.

The tendency for carbonates to become more calcitic with successive ages is apparently normal in most gold-quartz deposits of all geological ages in rocks of all types. The tendency is most marked in basic and intermediate igneous rocks and less marked in granitic rocks and sediments. Reversals of the trend have, however, been noted, but they are usually local.

Native gold, in contact with vein and wall-rock carbonates, is invariably late, occurring in seams, fractures, crushed zones and small slips. In some old (Precambrian) and young (Tertiary) deposits gold is sometimes found moulded on the scalenohedral prismatic and rhombohedral faces of carbonates, between crustified layers and in carbonate mineral vugs. Gold tellurides generally exhibit relationships to carbonate minerals similar to those for native gold.

Few colour relationships have been observed among the carbonates of gold deposits with respect to type of deposit or age of deposit. Black carbonates (mainly ankerite or calcite) are common in some Precambrian gold-quartz deposits. These carbonates are invariably associated with black and grey quartz and owe their colour to amorphous carbon in most places (Boyle, 1953). Reddish carbonates, stained by hematite, occur in certain gold deposits containing uranium minerals. The iron oxide appears to have been liberated from the carbonates in some manner or other by radioactive bombardment since the coloration often forms halos or streaks about the uranium minerals.

The microscopic features of vein carbonates in gold and other types of deposits are discussed in an excellent study by Grout (1946). Space does not permit a detailed summary of the results of this investigation here, but some general observations may be noted. Concerning sulphides in auriferous deposits Grout found a general trend (not without exceptions) for the presulphide carbonate to be mixed and complex, whereas the late carbonate is commonly calcite. The early carbonates are very commonly replaced by sulphides, whereas the late calcite fills minute fractures and only rarely replaces the sulphides. Grout noted the common occurrence of native gold with ankerite and along cleavage planes of calcite and other carbonates. In some deposits the carbonates associated with gold began forming early and continued even after the deposition of native gold. An exception to the general sequence of ankerite giving way to calcite during deposition in gold deposits was noted by Grout in the Howey Mine in the Red Lake district of Ontario where Mather (1937) observed that the early calcite deposited with the gold was calcite with ankerite increasing in proportion thereafter.

Smithsonite, the zinc carbonate, *cerussite*, the lead carbonate, and the two copper carbonates, *malachite* and *azurite*, are common in the oxidized zones of auriferous deposits containing primary zinc, lead and copper minerals. *Bismutite*, $(BiO)_2(CO_3)$, is common in the oxidized zones of auriferous deposits containing primary bismuth minerals. The carbonate is commonly associated with wires, hairs, spangles and finely divided particles of gold as in certain deposits in Honduras, Australia, U.S.S.R. and elsewhere.

Fluorite is a gangue mineral in some gold-quartz and polymetallic deposits. It is relatively rare in most of the skarn-type gold-bearing ores. Most Precambrian gold deposits are generally marked by their paucity of fluorite, but the mineral becomes increasingly abundant in younger deposits and is an important gangue mineral in some Tertiary deposits. Fluorite is not recorded as being present in the Witwatersrand bankets (Liebenberg, 1955; Saager, 1968; Feather and Koen, 1975). Various colours mark fluorite in gold deposits, from colourless to green, yellow, brown, reddish and violet-blue.

The veins of Cripple Creek, Colorado are exceptionally rich in violet fluorite which tends to crystalline forms (Lindgren and Ransome, 1906). There, as elsewhere in other gold deposits containing fluorite, quartz and carbonates are often highly intergrown or form remarkable crustified arrangements in the veins. Generally speaking fluorite, quartz, carbonates and sulphides are early minerals followed by gold and gold tellurides in depositional sequence. In crustified veins repetitions of the sequence are frequently present.

Halite occurs in a number of Precambrian deposits and in others where the underground waters are rich in sodium chloride. Occurrences in Canada are notable in the Con Mine, Yellowknife, in the Madsen Mine at Red Lake and in the Undersill Mine at Beardmore, Ontario. In most of these occurrences the halite is a late mineral localized in both crystalline and massive form along late slips and in small breccia faults. Both colourless and orange varieties have been observed; neither of these contain gold and silver (Au <0.005 ppm; Ag <0.1 ppm).

Other primary halide minerals are rare in auriferous deposits. The various silver halides including *chlorargyrite, bromargyrite* and *iodargyrite* may occur in the oxidized zones of gold-silver deposits in arid and semiarid climates or where there is an abundance of chloride, bromide or iodide in supergene waters. Copper halides such as *atacamite* have a similar distribution. The occurrence of these various halides with gold is considered in greater detail in Chapter IV.

Barite, celestite, anhydrite and *gypsum* are minor to major gangue minerals in some gold deposits, generally the gold-quartz type. Barite is rare in Precambrian deposits but is of increasing importance in younger deposits. Celestite is relatively rare, but the mineral occurs in some of the deposits at Kirkland Lake, Ontario, at Cripple Creek, Colorado and elsewhere. Anhydrite and gypsum appear to be relatively common in many gold-quartz deposits ranging in age from Precambrian to Tertiary. Both minerals are abundant in some of the veins in the Timmins (Porcupine) district of Ontario (Langford and Hancox, 1936). In the McIntyre Mine large zones of the quartz-feldspar porphyry are replaced by anhydrite. Some Tertiary gold veins are notable for the large amounts of barite and anhydrite they contain. In these deposits native gold and other gold minerals are paragenetically later than the two sulphates. In the paragenetic sequence of minerals in other gold deposits anhydrite and gypsum are generally later than both quartz and the first stage of carbonates, pyrite and arsenopyrite; in some wall-rock alteration zones, anhydrite appears to be about the same age as the replacement carbonates. With respect to gold and its minerals good relationships are rarely observed, but I have not seen gold in anhydrite or gypsum, which suggests that these two sulphates are probably very late minerals in some gold deposits.

Gypsum is a frequent mineral in the oxidized zones of auriferous deposits. Commonly gold is found in this mineral (selenite) in a wiry and dendritic form; also in bright spangles and as dust and mossy aggregates. Anhydrite is relatively rare in the oxidized zones of most auriferous deposits but has been noted in a few places.

Alunite, $KAl_3(SO_4)_2OH_6$, is a characteristic mineral of certain gold-quartz bodies and irregular silicified zones developed in volcanic sequences, usually dacite, latite, andesite and their equivalent volcanoclastics. Most of the deposits are of Tertiary age, although some occurrences are older, such as those in Mesozoic rocks on Vancouver Island (Clapp, 1915). Alunite is not known in deposits of Precambrian age.

Alunite occurs both in the wall rocks of the deposits as an alteration product and in the veins and irregular silicified zones. Characteristic examples occur at Goldfield, Nevada, at Rodalquilar in southeast Spain, and in the Kasuga Mine, southern Kyushu, Japan. The paragenetic relationships of alunite and gold minerals seem to be variable. In some cases the alunitization is paragenetically early and is followed by stages characterized by gold and silver; in a few deposits alunite, generally in small amounts, seems to have been deposited contemporaneously with native gold and gold tellurides. In some deposits alunite is commonly associated with *jarosite*, but the paragenesis of the latter is often difficult to ascertain. In most deposits it is probably of supergene origin, derived from the oxidation of pyrite.

The wall-rock alteration effects of alunitization are discussed in a following section.

Jarosites, including *argentojarosite*, are relatively common minerals in the oxidized zones of some auriferous deposits. *Anglesite*, the lead sulphate, and *brochantite* and *chalcanthite*, the copper sulphates, occur among the oxidized products of some auriferous deposits. These minerals are discussed in more detail in Chapter IV.

Apatite is often present in small amounts in various types and ages of gold deposits, but only in a few is it an important gangue mineral. Hulin (1930) mentions such a case in the Kennedy Mine of the Northern Lode System of California. Willimott (1884–1885) mentions gold in apatite near Péche Village, Wakefield Township, Gatineau County, Quebec. *Wavellite* is reported from some of the gold veins at Cripple Creek in Colorado and elsewhere. It may be a secondary (supergene) mineral in these deposits. Other phosphates are rare in gold deposits. Poznyak (1968) found *variscite* in a gold deposit in western Chukotka and Williams (1972) noted the presence of *embreyite*, $Pb_5(CrO_4)_2(PO_4)_2{\cdot}H_2O$, in specimens from the oxidized zones of the Beresov gold-quartz veins, Urals, U.S.S.R. These phosphates, in addition to *pyromorphite*, which occurs in certain plumbiferous gold deposits, are mainly supergene in origin. In the Bobrik auriferous lead-zinc deposits of the Donets Basin, U.S.S.R. Kuznetsov *et al.* (1973*a*) describe occurrences of *florencite*, a rare-earth–thorium phosphate. They claim that the rare-earth mineral can be used in prospecting when it is present in deposits. Aleksandrov *et al.* (1975) also found florencite in the carbonate-sulphide alteration zones of the Bodaibo deposits, eastern Siberia. *Monazite* is rare in most auriferous deposits particularly in the gold-quartz type. In the Rand the mineral occurs in only small amounts in the matrix of the conglomerates. According to Liebenberg (1955) the mineral is authigenic in origin in some bankets and detrital in others. Monazite is a universal associate of gold in recent placers.

Nolanite, $Fe_3V_7O_{16}$, appears to be relatively common in a number of gold deposits. The mineral occurs in the Nicholson deposits in the Goldfields area, Saskatchewan and in the deposits of the Golden Mile, Kalgoorlie, Western Australia. In the latter the nolanite is closely associated with native gold, various tellurides and vanadium muscovite (sericite) (Nickel, 1977). The vanadium is present in the trivalent state and is responsible for the green colour of the 'green leader'.

Numerous other phosphates, arsenates, vanadates and antimonates occur in gold deposits mainly in the oxidized zones. Among the most common of these are *pyromorphite-mimetite, vanadinite, scorodite, bindheimite* and *beudantite*. Where primary Ni-Co arsenides are present the supergene arsenates *annabergite* and *erythrite* may be present among the oxidation products. *Crocoite*, $PbCrO_4$, occurs in some of the oxidized parts of the veins in the Berezovsk goldfield, Urals, U.S.S.R. The occurrence of these minerals is discussed in more detail in Chapter IV.

Pyrite is the second most abundant mineral in gold deposits exceeded only by quartz. In some deposits pyrite may actually exceed quartz in quantity, as in certain skarn, polymetallic and massive sulphide deposits. All varieties of pyrite occur in gold deposits, including crystalline, massive, fine granular, radiating, reniform, globular ('buck shot') and stalactitic forms.

Gold occurs in pyrite in three forms – submicroscopic, perhaps in the lattice of the mineral; as native gold in small blebs, droplets and ramifying masses, generally at random; and as irregular masses, plates and grains along fractures, slips and seams or coating the faces of crystals. The first mode of occurrence is considered at length in the section on gold in other minerals in Chapter II. In many cases the second indicates exsolution; this mechanism is also discussed in Chapter II. The third indicates exsolution in some cases; in others introduction from sources outside the confines of the immediate pyrite crystal or pyritic mass is more probable. The source of this gold is considered in the section on the origin of gold deposits in this chapter.

Gold tellurides in contact with pyrite generally exhibit relationships similar to native gold. Most are late minerals occurring in fractures in individual pyrite crystals, in fractured parts of pyritic masses or perched on pyrite crystals.

In some auriferous ores the grain size of pyrite is indicative of the grade of the ore – the finer the grain size the higher the grade. Anhedral and subhedral pyrite are also commonly richer in gold than the euhedral sulphide. Large euhedral crystals of pyrite in deposits are generally low in gold, although, as usual, there are some exceptions to this observation. The reason for the enrichment of gold in fine-grained anhedral pyrite is not clear. In some cases it may be due to initial precipitation processes involving numerous sites for deposition of gold on pyrite nuclei; in other cases it may be related to crushing and mylonitization of the pyrite, followed by introduction of gold into the crushed and mylonitized zones.

Chesnokov and Popova (1971) studied the crystal morphology of pyrite from the Berezovo gold deposits of the Urals, U.S.S.R. The pyrite in the quartz veins, beresites and listwänites exhibited mostly a hexahedral, rarely a pentagonal-dodecahedral, crystal habit and formed essentially contemporaneously. Gold was found to be present in the form of small inclusions in the pyrite, the distribution of the metal increasing from the central to peripheral parts in large crystals (0.2–70 ppm Au). In undeformed crystals very small contents of gold were observed. In a somewhat similar study of the same deposits Chesnokov (1972) measured the paramater a_0 of pyrite. It was found to increase linearly with an increase in the Ni + Co content of the pyrite and also with an increase in the Ni content of the country rocks.

In the Kalba gold belt, Kazakhstan, U.S.S.R., Poltorikhin (1974*a,b*) noted six generations of fine-grained pyrite, the fifth generation (arsenic-gold-polymetallic stage) being the richest in gold. This pyrite tends to be complex and is often characterized by a pentagonal dodecahedral habit, outer layers ('jackets'), a zonal internal crystal structure, increased unit-cell parameters, the greatest mineral admixture (located along growth zones and microfractures), a lower microhardness and reflectivity and also a negative thermoelectric effect. In addition there is evidence of collective crystallization, the presence of several centres of crystallization and shifts in the angles of the growth zones, as well as cases of the recrystallization of globular pyrite into the crystalline variety. The gold-silver-rich pyrite is also said to exhibit the greatest number of defects in the crystal lattice.

In the Carlin and Cortez disseminated gold ores of Nevada, Wells and Mullens (1973) found by electron probe analysis that much of the gold in the unoxidized ores was concentrated together with arsenic in tiny pyrite grains (<0.005 mm) and in thin rims of larger pyrite grains scattered through the mineralized rock. No free gold was observed in the unoxidized ore, the particles being submicroscopic (<0.5 μ); in the oxidized ore, free gold is relatively abundant.

A number of investigations of the trace element content of pyrite in Canadian gold mines have been carried out, most with mixed results. Auger (1941) examined the minor element (Ag, Zn, Pb, Co, Ni, Cr, Pb, Ti, V, Sr and Ba) content of pyrite in a number of Canadian gold deposits. His results are too comprehensive to report in detail, but briefly he observed that (1) within one mine, one district or even one region, certain minor constituents show a consistent supremacy over other elements; (2) the type of ore deposit or the temperature of deposition has affected the nature of the accessory elements; (3) the nature of the wall rock has no apparent effect on the distribution of the minor elements in pyrite; (4) gold in the sulphide has a very erratic distribution; and (5) most of the elements found in pyrite except gold are part of the pyrite lattice.

Auger (1941) also made a systematic analysis of hundreds of sulphide samples from the Hollinger, Noranda and Siscoe mines. The samples taken at regular level intervals in the mines showed that: (1) there is a systematic variation with depth in the quantities of minor elements; (2) the type of variation does not agree with the usual zonal precipitation of minerals; and (3) the vein type of deposits gives more erratic values for the minor elements than does the massive sulphide types of deposits.

Hawley (1952) studied the distribution of Au, Ag, Te, Ni, Co, Pb, Zn, Sn, Mo, Mn, Cr, Ti, V, Bi and As in pyrite from four Canadian gold deposits in Ontario (Kirkland Lake area, Porcupine area) and Quebec (Powell-Rouyn Mine). Among other parameters variations in the concentration of the trace elements with depth, size of grain, host rock and matrix, vein type and temperature as determined with the pyrite geothermometer (Smith, 1947) were studied. The only persistent variation in composition of pyrite with depth noted was an increase in the cobalt content. Otherwise, excepting a few local variations, a uniformity in the trace elements to depths of 5000 ft were notable. Variations with other parameters appeared to be erratic, although there was a general consistency in the presence of tellurium in the pyrite from the Kirkland Lake area and its rarer occurrence in the other deposits.

Hawley and Nichol (1961) carried out a detailed study of trace elements (Co, Ni, Ag, Cr, Pb, Sn, Ti, V, Au, As, Bi, Mn and Mo) in pyrite from the Sudbury, Flin Flon, Chibougamau, Quemont, Noranda, Normetal, Manitouwadge and McIntyre deposits, all of which contain gold in minor or major amounts. Qualitatively the pyrite contained much the same suite of elements as pyrrhotite and chalcopyrite from the same deposits. Gold showed a greater preference for pyrite than pyrrhotite or chalcopyrite. Cobalt was preferentially concentrated in the order pyrite, pyrrhotite and chalcopyrite, the usual order of crystallization of these minerals in the ores.

The distribution of nickel was much less regular than cobalt in the three sulphides. With respect to silver in the three sulphides, chalcopyrite was always richer than pyrite or pyrrhotite. Other elements showed no regular or systematic differences in distribution in the three sulphides. Variations in the quantities of trace elements were noted in deposits of different as well as of similar types. Variations were also evident in the varieties of pyrite at McIntyre, in pyrite of different generations, in pyrrhotites of different generations, and in pyrrhotites of differently located orebodies, as at Sudbury. Variations also occurred with depth in certain ore shoots.

The writer has carried out trace element studies of pyrite in the gold deposits at Yellowknife, in those at Keno Hill and elsewhere. He has concluded that no particular patterns are indicated with respect to oreshoots within a single mineral belt or with depth. The reason for this is evidently due to the fact that pure pyrite cannot be separated from orebodies. It always contains wisps, blebs and patches of most of the ore minerals in the deposits in varying proportions. The trace element data, therefore, only indicate the degree of contamination of the pyrite by other ore minerals. Unless special procedures are taken, such as acid leaching, to remove these extraneous minerals the trace element data are erratic. Even these procedures are not satisfactory in most cases because pyrite cannot be ground fine enough. There are, however, some general qualitative relationships that are immediately observable in the trace element content of pyrite between different mineral belts as Auger, Hawley and Nichol and others have pointed out. Tellurium appears in greater abundance in some ores such as those at Kirkland Lake, and silver and gold are in general more abundant in pyrite in auriferous deposits than in those that are barren of the two metals. The nickel and cobalt contents and the Ni/Co ratio may also be indicative of certain types of orebodies and may also have depth significance. However, if these elements and their ratio are to be used effectively, pyrrhotite, arsenopyrite and minerals such as tetrahedrite and Ni-Co arsenides must be effectively removed completely from the pyrite before analysis.

My observations indicate that relatively high arsenic and antimony contents in pyrite are often an indication of enrichment of gold in auriferous deposits. This is a general statement, and not all deposits may show this effect. The reason may lie in the probability that much of the gold in endogenic processes migrates as an Au-As-S or Au-Sb-S complex as outlined in Chapter II.

Pyrite was used by Wanless *et al.* (1960) for isotopic studies of sulphur in the Yellowknife gold-quartz deposits. No systematic variations in the $^{32}S/^{34}S$ ratios were observed with depth in the mines, but some variations were noted in the pyrite from different ages and types of deposits and occurrences. These are discussed further in the section on origin of deposits in the last part of this chapter.

Pyrite is the most abundant metallic mineral in the gold-bearing quartz-pebble conglomerate reefs of the Witwatersrand in South Africa and Jacobina in Brazil; also in the uranium–thorium–rare-earth–bearing conglomerates of the Elliot Lake district, Ontario, Canada. In these three deposits one is justified in saying that with some slight modifications the nature and occurrence of pyrite is similar in all three deposits. The pyrite of the Witwatersrand has been extensively studied by Liebenberg (1955), Ramdohr (1958 *a,b*), Saager and Mihálik (1967) and Feather and Koen (1975). Saager (1970) has produced a table, which is self explanatory of the types of pyrite present in the Rand (Table 42). Most of the gold in the Rand bankets is not detrital in its present form. In its relationships with pyrite the authigenic or secondary gold is only rarely found as inclusions in the pyrite. Liebenberg (1955, p. 161) remarks that:

> Although gold is a relatively constant and widespread associate of the pyrite in the banket, this sulphide is only of secondary importance as a gold carrier. Mineragraphic work on specimens of the banket, and on pyrite concentrates, shows that amongst the tens of thousands of grains examined, only comparatively few of them contain included gold. Where present, the gold is found mainly as minute roundish and irregular inclusions in grains of buckshot pyrite, but relatively large irregular patches and veinlets of gold replacing the grains of pyrite were also observed. Replacement of pyrite by gold is sometimes indicated by minute stringers leading from the irregular inclusions of gold into the pyrite host. Cracks in the pyrite are occupied by gold. Occasional grains of pyrite are partly enveloped by thin films of gold from which fine stringers sometimes lead into the pyrite along microscopic fissures.

Saager (1969) mentions that:

> Frequently the gold, during its reconstitution, has migrated into the marginal areas of porous pyrite grains where it now forms secondary inclusions. Primary inclusions and myrmekitic intergrowths of gold with detrital pyrite and linnaeite have occasionally been observed.

Table 42. Different pyrite structures in the Basal Reef in the Orange Free State Goldfield, South Africa

Morphology	Structures	Allogenic	Authigenic
Rounded	Compact or porous	Detrital pyrite and black sands pyritized before their final deposition	Black sands pyritized *in situ*
	Pseudomorphic	Inhomogeneous black sands pyritized before their final deposition	Inhomogeneous black sands pyritized *in situ*
	Concretionary		Generally formed *in situ;* very rarely signs of short transportation
	Nodules containing 'mineralized bacteria'		Formed *in situ;* indicating presence of primitive life
Idiomorphic to hypidiomorphic	Compact or porous		Formed *in situ* by reconstitution of ferrous sulphide; rarely hydrothermal along dyke contacts
	Compact or porous encrustations		Formed *in situ* by reconstitution during metamorphism; generally overgrow older detrital pyrite
Xenomorphic	Veinlets and fracture fillings		Formed *in situ* by reconstitution during metamorphism

Source: Saager (1970).

Some varieties of buckshot pyrite in the Rand are relatively rich in arsenic (0.2–0.9%) and in nickel and cobalt (Ni – 0.1–0.4%; Co – 0.05–0.02%) (Saager and Mihálik, 1967). According to the present writer, investigations of all varieties of pyrite in the samples from the Rand and Elliot Lake that have been analyzed contain relatively high amounts of As, Sb, Ni, Co, Cu, Pb, Mo, Cd, Zn, W, Ag, Au, Hg, Te and Se. Some of these elements may be in the other sulphides and minerals that cannot be physically separated from the pyrite.

While pyrite is a fair indicator of the presence of gold in quartz-pebble conglomerates it is not an invariable one. Von Rahden and Urli (1969), who carried out a statistical treatment to determine the correlation of gold, uranium and pyrite in some of the reefs of the Rand, concluded that in certain reefs there is a significant correlation of the two elements with pyrite; in others the correlations are not significant.

Marcasite occurs in many types of auriferous deposits, but it is rarely differentiated from pyrite, and hence its exact paragenesis is relatively unknown. The mineral appears to be most common in the younger deposits, particularly those of Tertiary age. In these deposits marcasite is commonly an early mineral often accompanying or taking the place of pyrite. In all deposits marcasite continues to be precipitated from time to time during the mineralization process; in places it is a very late mineral lining fractures, small faults and slips that cut the gold orebodies. In these occurrences it is usually accompanied by calcite and is barren of gold.

Arsenopyrite accompanies gold in all types of its deposits. It is particularly common in Precambrian, Paleozoic and Mesozoic deposits, less so in Tertiary deposits. The relationships of arsenopyrite, gold, aurostibite and gold tellurides in deposits are essentially the same as those for pyrite and need not be repeated. In many deposits there is frequently a much closer association between gold and arsenopyrite than between the precious metal and pyrite, a feature emphasized by the frequent necessity to fine-grind and roast auriferous arsenopyrite ores to liberate the mineral in a form amenable to cyanide treatment. In some deposits even this treatment is not entirely satisfactory, since the gold is either submicroscopic or a lattice constituent of the arsenopyrite.

In some ores the grain size of arsenopyrite is indicative of the grade of the ore. At Yellowknife and elsewhere the finer the grain size of the arsenopyrite in some ore shoots the higher is the grade. The reason for this is not clear. In some cases it may be due to initial precipitation processes involving numerous sites for the deposition of gold on arsenopyrite nuclei; in other cases it may be related to crushing and mylonitization of the arsenopyrite, followed by introduction of gold into the crushed and mylonitized zones.

Arsenopyrite is a common mineral in gold-bearing quartz-pebble conglomerates although the amounts present are usually low (generally 1%). In the Witwatersrand Liebenberg (1955) mentions that gold particles occur in arsenopyrite more frequently than in pyrite. He has concluded that the arsenopyrite is a younger mineral, paragenetically speaking, than pyrite. Feather and Koen (1975) class arsenopyrite as an allogenic mineral in the Rand ores. They found up to 3 per cent Co and/or Ni in the mineral.

Some gold deposits contain massive shoots of arsenopyrite. Such deposits are known in the eastern Ontario gold belt (Marmora, Deloro, Actinolite), near Hedley British Columbia (Nickel Plate Mine), in the Bau gold district of Sarawak and elsewhere. In many of these deposits native gold is rarely visible, and considerable difficulty is encountered in winning the metal from the ores. In the Carlin and Cortez disseminated gold ores of Nevada, gold is intimately associated with arsenopyrite in an invisible form in the unoxidized ores (Wells and Mullens, 1973).

The presence of arsenopyrite or pyrite in deposits is not an invariable guide to gold mineralization, although it can be said that both minerals are favourable indicators, particularly in the gold-quartz and disseminated types of ores. There are, however, many of these deposits often with abundant pyrite that are practically devoid of gold. In the writer's experience, most deposits containing arsenopyrite appear to be enriched in gold, although the amounts may not be economic.

Both pyrite and arsenopyrite may be constituents of recent auriferous placers.

Pyrrhotite is present in nearly all types of gold deposits, being particularly common in those of Precambrian, Paleozoic and Mesozoic age. In Tertiary deposits, particularly those noted in the older literature as epithermal deposits, the mineral is relatively rare. The relationship of gold, aurostibite, gold tellurides and pyrrhotite are essentially the same as those for pyrite and need not be repeated.

According to Ebbutt (1948) pyrrhotite is much less commonly auriferous, a feature also noted by Dougherty (1935), Hawley and Nichol (1961) and others. Ebbutt thinks that this is due to the fact that pyrrhotite is prone to mash and recrystallize whereas pyrite, being brittle, holds fractures readily and allows the late gold to enter the fractures. Certainly, pyrrhotite exhibits a rather erratic behaviour with respect to its gold content in the writer's experience, a feature also commented on by Dougherty (1935) and Schwartz (1944).

In the Witwatersrand quartz-pebble conglomerates, pyrrhotite is present generally only in small amounts. Pelletier (1940) found a marked association between gold and pyrrhotite in these ores. Pyrrhotite concentrates show about twice as much gold as those of pyrite, which is much more abundant in the ores. The same author mentions that under the microscope gold also appears more commonly in pyrrhotite than in pyrite. According to Liebenberg (1955) pyrrhotite is a secondary (remobilized) sulphide, as are also galena, sphalerite, chalcopyrite, etc., and he agrees that gold is more commonly associated with these sulphides than with the paragenetically older pyrite. Feather and Koen (1975) state that some investigators have found no obvious relation to exist between pyrrhotite and gold.

Chalcopyrite generally accompanies gold in its deposits, the amount present being variable – minor quantities in gold-quartz deposits and minor to major amounts in polymetallic and skarn ores. In some gold-quartz deposits chalcopyrite is a good indicator of gold values; in others there is no particular relationship.

The relationship of gold to chalcopyrite is much the same as that described for pyrite and arsenopyrite. The gold may be present (1) in a submicroscopic form, probably in the lattice of the mineral, (2) in blebs and irregular masses in the mineral, the particles of gold having no particular orientation or relationships and (3) in seams, small cracks and fractures, and surrounding, penetrating and moulding the surfaces of the mineral grains. Gold occurs in its various forms in chalcopyrite for the same reasons as those given above for pyrite. The evidence is, however, stronger that gold (and silver) replace copper in the structure of the mineral because of the size of the atoms and other considerations discussed in Chapter II. This is commonly the relationship in chalcopyrite in some polymetallic, skarn and massive sulphide deposits.

Gold tellurides are usually paragenetically later than chalcopyrite. At Kirkland Lake the tellurides commonly occur in fractures in chalcopyrite and replace it extensively in places. The paragenesis of the tellurides in the Cripple Creek ores is complicated to say the least, but these minerals are generally later than the small amounts of chalcopyrite present in the ores (Lindgren and Ransome, 1906). In the complex seleniferous gold ores of Salida, Indonesia, the gold and other tellurides are later than chalcopyrite (Kieft and Oen, 1973).

In the Rand ores Liebenberg (1955) mentions that gold frequently occurs in chalcopyrite; however, usually only in small amounts. Feather and Koen (1975) state that chalcopyrite in the Rand is intimately associated with gold and sulphides, e.g., pyrrhotite, pentlandite and sphalerite, of the same paragenesis.

Sphalerite and *galena* are nearly universal minerals in gold deposits of all types, the amounts of the two minerals ranging from mere traces to several per cent. Sphalerite is the more abundant of the two minerals in most deposits.

Large amounts of galena are relatively rare in Precambrian deposits, especially those of Archean age. Younger deposits generally contain more galena, but the amounts are often highly variable from belt to belt and in different types of deposits.

Galena is generally paragenetically younger than pyrite, pyrrhotite and arsenopyrite in most types of gold deposits and often appears to have crystallized at or about the same time as gold. In many deposits the mineral is, therefore, a good indicator of gold values, a feature noted by numerous investigators (Schwartz, 1944). The same statements also apply to sphalerite, although this mineral is perhaps less indicative of good values in some deposits. One of the reasons why galena and gold are commonly associated in nature may be due to certain epitaxial relationships that exist between native gold and the lead sulphide.

The paragenetic and age relationships of gold, gold tellurides and aurostibite with respect to galena and sphalerite are not always clear-cut in gold-quartz, skarn and polymetallic deposits. In some ores the gold minerals occur as blebs, droplets and irregular masses in the two minerals and appear either to be exsolved constituents or to have crystallized together. The frequent occurrence of gold and other tellurides in or associated with galena is notable in places. The tellurides may have exsolved from the galena, replaced the galena or the minerals may have been coprecipitated together in some manner or other. All of these relationships probably are related to the fact that galena, PbS, and altaite, PbTe, are similar structurally and not greatly different from some of the bismuth, gold and silver tellurides in some of their parameters. There are, however, numerous references in the literature describing gold and gold tellurides in veinlets that occur in fractures in both galena and sphalerite, and gold frequently occurs along the cleavages of galena. Replacement of galena and sphalerite by gold is also commonly referred to, and veinlets of gold, gold tellurides, galena, sphalerite, chlorite, sericite and clear quartz commonly intersect pyrite and arsenopyrite. In crustified veins, gold and gold tellurides commonly occur along the crystal faces of galena and sphalerite, in crystal vugs of the two minerals and perched on crystals of the two sulphide minerals. In the complex seleniferous banded gold ores of Salida, Indonesia, the gold and other tellurides are closely associated with the bands of galena and fine-grained sphalerite (Kieft and Oen, 1973). In summary, most of the gold minerals in gold-quartz, skarn and polymetallic deposits are either contemporaneous with galena and sphalerite or later than these two minerals.

Liebenberg (1955) notes that gold frequently occurs as inclusions and replacement bodies in the small amounts of galena and sphalerite in the bankets of the Rand. Both of the base metal sulphides are paragenetically younger than the bulk of the pyrite. Feather and Koen (1975) class sphalerite as a consistent authigenic mineral in the reefs.

Stibnite is a relatively common mineral in gold deposits of the gold-quartz, polymetallic and disseminated type. The mineral is rare or absent in most skarn deposits seen by the writer. No age differences in the occurrence of stibnite have been noted by the writer, nor are any mentioned in the literature. Some Precambrian deposits (e.g., Yellowknife and Red Lake, Canada; Murchison Range, South Africa) are rich in stibnite, as are also some deposits in Paleozoic (West Gore, Nova Scotia; Costerfield, Victoria, Australia), Mesozoic and Tertiary rocks (Hauraki, New Zealand). Recent hot springs precipitating stibnite, also deposit gold in places. Some gold-bearing stibnite deposits have been mined mainly for antimony with gold as a byproduct (e.g., Murchison Range, South Africa).

Stibnite is not mentioned as being present among the ore minerals of the Witwatersrand (Saager, 1968), but Feather and Koen (1975) have recently identified the sulphide in a rough platinoid concentrate from Western Deep Levels, Limited.

In the disseminated ores of Carlin, Cortez and Gold Acres in Nevada, stibnite is the principal antimony mineral.

Stibnite is invariably a late mineral in gold deposits. At Yellowknife it occurs with gold in late fractures, as nests in crushed parts of the quartz veins and in vuggy parts of the veins. In the Red Lake deposits it is, likewise, late occurring in much the same manner as at Yellowknife. Horwood (1945) places it among the latest minerals deposited in the Cochenour Willans Gold Mine. Stibnite is also late at West Gore in Nova Scotia, in the Paleozoic auriferous deposits in France and in most of the other samples of stibnite-bearing gold ores seen by the writer. In young (Tertiary) deposits successive generations of stibnite and gold may occur in crustified veins.

The relationship of native gold and gold tellurides to stibnite are not always clear. Deposition of the gold minerals and stibnite in most deposits appears to be contemporaneous or nearly so. Native gold often occurs as blebs and droplets in massive stibnite, and some relationships suggest replacement of stibnite by gold. Occasionally one sees veinlets of native gold in broken blades of stibnite, and in some vugs gold is perched on stibnite crystals. Otherwise, stibnite and gold have mutual relationships and appear to have crystallized together.

The tellurides generally show the same relationships to stibnite as native gold when found together.

Aurostibite, $AuSb_2$, commonly occurs in stibnite-bearing gold veins. At Yellowknife the relationships of the mineral and stibnite are not clear. Most of the aurostibite rims or penetrates gold particles along small fractures. It appears to be later than the gold and stibnite, and probably also the sulphosalts. In some stibnite ores in the Canadian Shield where gold is present in close proximity to the stibnite, the particles of the metal have a peculiar brownish colour that may be due to incipient formation of aurostibite. Metallurgists believe that this gold resists amalgamation and cyanidation. Aurostibite is also known in the ores of the Chesterville Mine, Larder Lake, Ontario; in the gold deposits of Krasna Hora and Milesov in Czechoslovakia; in the antimony veins of Costerfield, Victoria, Australia; and in the Lone Hand and Jessie gold mines, Gwanda District, southern Rhodesia; also in a number of auriferous-antimoniferous belts in U.S.S.R. In all of these occurrences the aurostibite is late – it precedes, accompanies or follows gold in the paragenesis of the vein minerals. (*See also* the section on the mineral in Chapter II.)

Niccolite, cobaltite and *cobaltian loellingite* are relatively rare in gold-quartz, gold-bearing skarn and polymetallic deposits. In the Rand ores they occur together with minerals such as glaucodot, bravoite, millerite, pentlandite, linnaeite, gersdorffite, skutterdite and safflorite, in small amounts (Saager, 1968; Feather and Koen, 1975). Most of these minerals are authigenic (remobilized) minerals and are commonly associated with similarly reconstituted gold. Some investigators have noted a striking affinity between Ni-Co minerals, especially cobaltite, and gold in the Witwatersrand ores (Liebenberg, 1955; and others). Saager (1968), however, did not notice the intimate association of cobaltite and gold in the Basal Reef of the Orange Free State Goldfield and thinks that the cobaltite occurs mainly as water-worn detrital grains. Feather and Koen (1975) recognized two distinct generations of cobaltite and gersdorffite in the reefs – one allogenic and the other authigenic.

In some skarn bodies such as those of the French Mine at Hedley, British Columbia, safflorite and cobaltite occur in the ores, but the age relations of the gold and these minerals are not entirely clear. The gold appears to be paragenetically later than the Ni-Co sulphides and arsenides in most cases. Krieger and Hagner (1943) reported similar relationships with respect to the gold-bearing nickel minerals at Alistos, Kinaloa, Mexico. In the Soviet Union a number of the auriferous skarns carry small to moderate amounts of a number of nickel-cobalt minerals, including *gersdorffite, cobaltite, danaite, glaucodot* and *safflorite*. These are generally early minerals in the paragenetic sequence in the deposits. According to Byers (1940) cobaltite is a much earlier mineral than gold in the Nighthawk Peninsular Gold Mine in the Timmins area of Ontario. In the Ross Gold Mine at Ramore, Ontario, the age of the cobaltite and gold is not clear. The same is true where small amounts of Ni-Co arsenides occur in some of the gold mines (Algold Mine) in the Goudreau-Michipicoten area of Ontario. At the Mackinaw Mine, Snokomish County, Washington, the gold is later than niccolite and pentlandite and is always associated with maucherite ($Ni_{11}As_8$) (Milton and Milton, 1958).

It is of interest to note that veins with abundant native silver and Ni-Co arsenides and sulphides, such as those at Cobalt and elsewhere, contain relatively little gold. The ores at Cobalt contain only <10 to 100 ppb Au on the average. Certain similar Ni-Co arsenide deposits generally with low amounts of silver and commonly with pitchblende or uraninite may be enriched in gold. An example of this type of deposit is found at Cluff Lake in the Carswell structure, northern Saskatchewan. There, the veins contain abundant uraninite and colloform pitchblende, native gold, gold tellurides, clausthalite, chalcopyrite and nickel-cobalt sulpharsenides, mainly gersdorffite. The paragenesis of the gold with respect to these various minerals is uncertain; it appears in most cases to be a late mineral. Some of the Ni-Co arsenide veins at Bou Azzer in Morocco are auriferous, the gold being commonly intimately associated with maucherite and niccolite often in inclusions in the latter (Caillere and Dietrich, 1966).

Molybdenite is a common mineral in gold ores of all types, but is generally present only in very small amounts. It is noted among the ore minerals of the Rand by Saager (1968). The mineral appears in deposits of all ages from Precambrian to Cenozoic. It seems to be most frequent in those of Precambrian and Tertiary age.

Gold-bearing skarn bodies usually contain molybdenite, but the age relationships with native gold and gold tellurides are frequently difficult to ascertain, since the minerals are not often contiguous. Probably gold is later than molybdenite in most skarn bodies.

In gold-quartz and polymetallic ores, molybdenite is often late occurring along late slips and fractures. In this respect some molybdenite may be closely related paragenetically with gold and gold tellurides, although these minerals and the sulphide are rarely contiguous. At Yellowknife no good relationships between the gold minerals and molybdenite could be observed except in one vein where the gold appears to be contemporaneous or slightly younger than the sulphide. The molybdenite in the veins at Yellowknife investigated by the writer is predominantly the 2H type; only in the auriferous porphyry at the Con Mine at Yellowknife is the molybdenite of the 3R type (Traill, 1963; Boyle, 1968*c*). Another locality where 3R type molybdenite occurs is in some veins near Heron River, northern Ontario.

In some deposits molybdenite is commonly intergrown with pyrite, sphalerite or galena, indicating that it is perhaps paragenetically older than gold and gold tellurides. At the War Eagle Mine, Rossland, British Columbia, gold commonly impregnates molybdenite, but the age relationships are not entirely clear. Late generations of quartz seem, in some places, to bring molybdenite into various deposits. These appear to be younger than the last generation of gold and gold tellurides, since they do not contain gold minerals in most places.

Saager (1968) says that the molybdenite in the Rand always occurs as idiomorphic inclusions in rounded pyrite grains, which he thinks are allogenic components of the bankets.

Bismuth-bearing minerals, including *bismuthinite, matildite, cuprobismutite, tellurobismuthite, tetradymite, joseite, volynskite, cosalite* and a number of other bismuth sulphosalts, are recorded from many gold deposits, mainly the skarn, gold-quartz and polymetallic types. These minerals tend to

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occur more frequently in ores younger than Precambrian, although the element bismuth is generally recorded in all the Archean gold deposits, particularly in minerals such as galena and sulphosalts. Bismuth tellurides, native bismuth, bismuthinite and bismuth sulphosalts have all been recorded from Archean deposits. Some Proterozoic gold deposits are also notably enriched in bismuth.

In the ores of Goldfield, Nevada, (Tertiary) bismuthinite is relatively common and is accompanied by a bismuth-bearing variety of tetrahedrite (goldfieldite). The rich ores average 0.35 per cent Bi (Lindgren, 1933). The Tertiary ores of Boise Basin, Idaho, contained abundant galenobismutite, and this and other bismuth minerals were often intergrown with gold. According to Schwartz (1944) bismuth indicated good gold values in the Boise district. In the gold and silver-bearing sulphide of the Ohio mining district, Marysvale, Utah, bismuth minerals and cassiterite are relatively abundant. The principal bismuth minerals in these ores are cuprobismutite and bismuthinite. The native gold is paragenetically later than cuprobismutite (Radtke *et al.,* 1967).

Bismuth and bismuthinite accompany gold in the old Windpass Mine, British Columbia, and galenobismutite, bismuthinite and cosalite are common in the Cariboo Gold Quartz Mine at Wells, British Columbia (Warren, 1936). Bismuthinite occurs in some of the gold-quartz veins at Yellowknife, Northwest Territories.

In France, bismuth and bismuthinite are common in the gold ores of the Salsigne-Aude district (Tollon, 1970). In U.S.S.R. bismuth minerals accompany gold in a number of deposits in age from Paleozoic to Tertiary. Volynskite occurs in some of the gold deposits of Central Asia (Markova, 1967), and a number of bismuth minerals, including cosalite, native bismuth, bismuthinite, tellurobismuthite, tetradymite, wehrlite, galenobismutite, lillianite and emplectite are found in the Darasun gold field and Sredniy Gologtay deposits (Sakharova, 1969*b*, 1972; Sakharova and Krivitskaya 1972). In these deposits the bismuth minerals accompany the native gold, or the gold preferentially replaces the bismuth minerals. In any case there is a very close paragenetic relationship between gold and bismuth. Cosalite is reported from the gold ores of Berezovsk and Kochkarsh, Urals, U.S.S.R. (Vertushkov *et al.,* 1972).

Stillwell and Edwards (1941) report the occurrence of native bismuth in the gold ores of Tennant Creek (Precambrian) and native bismuth and galenobismutite in those at Cobar (Paleozoic) in Australia. Maldonite the black gold of some Australian mines (Maldon Mine, Victoria) is a mixture of gold and bismuth. The mineral also occurs in some greisen and skarn deposits. More recent research on the Tennant Creek ores has shown that the new mineral *junoite,* $Bi_8Pb_3Cu_2(S,Se)_{16}$, is the most abundant bismuth-bearing mineral at the Juno Mine (Large and Mumme, 1975; Mumme, 1975; Mumme and Watts, 1976). It is accompanied by the bismuth-selenium sulphosalt, *wittite,* and a variety of other selenium-bearing sulphosalts.

A few bismuth-bearing minerals have been recorded from the ores of the Witwatersrand (Feather and Koen, 1975). They include the platinoid minerals michenerite, moncheite and geversite. (*See also* the discussion on the native plantinoids in this section.)

These occurrences indicate the widespread distribution of bismuth minerals in gold deposits throughout the world. In general native gold and tellurides are later than or contemporaneous with most of the bismuth minerals. In some occurrences gold and native bismuth occur in an intergrown manner such as to suggest some sort of unmixing phenomena. Samples of native gold from numerous occurrences also contain traces to minor amounts of bismuth indicating that the two elements probably migrate together and are contemporaneously precipitated. There is also a frequent association of gold tellurides with various bismuth minerals, particularly bismuth tellurides and tetradymite.

In the oxidized zones of auriferous deposits containing hypogene bismuth minerals there is commonly an association of gold with supergene bismuth minerals such as bismite, bismoclite and bismutite. Such occurrences are reported from Honduras, Australia, U.S.S.R. and elsewhere. These minerals may also accompany gold in recent placers where they coat or are otherwise associated with native bismuth, bismuthinite and other bismuthian minerals.

Cinnabar is a relatively uncommon mineral in most gold deposits. It is particularly rare in skarn type deposits and has not been recorded in the Rand ores despite the fact that the latter are relatively high in mercury (Table 35).

Cinnabar is present in a number of gold-quartz and polymetallic deposits, some cutting rocks as old as Precambrian. Lindgren (1933) mentions the presence of the mineral in the veins of California (Mother Lode) and in those in central Idaho. Cinnabar is also common in some of the gold-bearing veins in Archean rocks in Rhodesia, mainly in carbonated andesitic lavas (greenstones) (Robertson, 1972); also in the Murchison Range, South Africa (Sahli, 1961). The mineral also occurs in some low-grade gold deposits in Grenville rocks near Clyde Forks, Ontario. Elsewhere, cinnabar is met with in small amounts in a number of Tertiary gold deposits throughout the world, examples being Cripple Creek in Colorado and a number of deposits in the far eastern U.S.S.R. Cinnabar occurs in small amounts in the disseminated ores of Carlin, Nevada (Radtke *et al.,* 1972*a,b*). Cinnabar, metacinnabar and gold are associated in the active solfataras of the Mendeelev volcano in the Kurile Islands (Ozerova *et al.,* 1969).

The age relationships of gold and cinnabar are not clear from most of the descriptions in the literature. Evidently, both gold and cinnabar are late minerals and may in part be contemporaneous. This is suggested by the common occurrence of mercury in native gold from many areas. In the Chinkuashih gold-copper deposits in Taiwan cinnabar and native sulphur are the last minerals to be deposited (Huang, 1973).

Supergene cinnabar is present in small amounts in the oxidized zones of certain auriferous deposits carrying mercuriferous tetrahedrite. The cinnabar evidently derives from the oxidation of the sulphosalt.

Cinnabar may accompany gold in certain placers, generally in mercuriferous belts.

Realgar and *orpiment* are rarely if ever found as hypogene minerals in gold deposits of Precambrian age. In younger deposits they appear with increased frequency and are common in some of the gold-quartz veins and disseminated deposits of the Tertiary. The realgar in the deposits at Nagyág in Romania is probably of hypogene origin, although some writers have considered it to be a supergene mineral.

In the disseminated ores of Carlin and Getchell in Nevada hypogene orpiment is relatively common, some of it being thallium-bearing (Radtke *et al.,* 1974*a*). Realgar is also present in these deposits. The auriferous Tertiary quartz vein at Zarehshuran in western Iran renowned for its orpiment, contains some realgar, stibnite, cinnabar, sphalerite, galena, jordanite, getchellite ($AsSbS_3$) and fine-grained black pyrite. The pyrite carries the bulk of the gold (Bariand and Pelissier, 1972). Present day hot springs depositing gold in the Taupo volcanic zone of New Zealand commonly contain up to 2 per cent arsenic, some of which is probably bound as orpiment (Weissberg, 1969).

The paragenetic relationships of realgar, orpiment and gold minerals are rarely mentioned in the literature. In general, the arsenic sulphides and gold minerals are late; in some deposits the minerals are essentially contemporaneous in age; in others gold is slightly younger than the arsenic sulphides. At Carlin, Nevada the orpiment and realgar together with stibnite and cinnabar are apparently later than the gold mineralization (Harris and Radtke, 1974).

Some of the realgar and orpiment in the zones of oxidation and reduction in auriferous deposits may be of supergene origin.

Argentite (acanthite), chalcocite and *stromeyerite* have a varied occurrence in gold deposits. *Argentite (acanthite)* is relatively rare in Precambrian deposits but common in younger deposits especially in the great gold-silver bonanzas of the Tertiary, classic examples being the celebrated Comstock Lode in Nevada and the veins at Tonopah, Nevada. Elsewhere in the world argentite-gold-quartz veins are or were mined extensively in Mexico, Japan, U.S.S.R. and New Zealand (Hauraki field). Argentite is generally a late mineral in auriferous deposits, and in many places it appears to have been deposited nearly contemporaneously with gold and its minerals. In some deposits gold is slightly later than argentite.

Primary *chalcocite* is not particularly common in any type of gold deposit. It is present in many auriferous skarn-type deposits, in various vein and porphyry-type deposits such as those at Butte, Montana and in a great variety of other types of deposits mined essentially for copper. The mineral is rare among the ore minerals of the Witwatersrand (Feather and Koen, 1975). The great supergene chalcocite bodies in many porphyry and other types of copper deposits are commonly enriched in both gold and silver. *Digenite* accompanies gold in the uraniferous deposits of Cluff Lake in the Carswell structure, northern Saskatchewan.

Stromeyerite, the silver copper sulphide, has about the same distribution in gold deposits as that mentioned for argentite and chalcocite. Some stromeyerite in deposits is a very late mineral and may actually be of supergene origin. Saager (1968) lists stromeyerite among the ore minerals of the Rand. It occurs near dykes crosscutting the Basal Reef in the Orange Free State Goldfield.

Bornite is not a particularly characteristic mineral of gold deposits, although it occurs in many types ranging in age from Precambrian to Mesozoic. It is not common in Cenozoic (Tertiary) deposits.

Bornite is probably most common in skarn-type deposits and gold-quartz veins. In the former it may be abundant, in the latter the mineral is generally an accessory, although in places, as in the auriferous disseminated copper orebody of the McIntyre Mine in the Timmins area, the sulphide is fairly abundant. The mineral is rare among the ore minerals of the Rand (Feather and Koen, 1975).

Cubanite has been recorded from a few gold deposits ranging in age from Precambrian (Morro Velho, Brazil) to Tertiary (far eastern U.S.S.R. gold belt). Paragenetically it appears at about the same stage as chalcopyrite. Cubanite is a very rare mineral in the reefs of the Rand (Feather and Koen, 1975).

Alabandite, MnS, is largely restricted to Tertiary gold deposits or to those of older age formed apparently at low temperatures. The mineral is invariably associated with veins rich in other manganese minerals such as rhodochrosite, rhodonite, johannsenite, inesite, etc. Alabandite occurs in the Tertiary gold and silver veins in Romania (Kapnik, Offenbánya and Nagyág), in Turkey, in Mexico and in Japan, and is relatively widespread in the western United States (Tombstone, Bisbee, Eureka Gulch and elsewhere). Some of these occurrences are described in more detail by Hewett and Rove (1930).

Albandite is generally earlier than native gold and its minerals in most deposits, but in some it appears to be nearly contemporaneous.

The *telluride* minerals are characteristic of nearly all types of gold deposits. They have not, however, been recorded in the disseminated deposits at Carlin and elsewhere in Nevada (Radtke *et al.,* 1972*a*). Deposits greatly enriched in base metal and precious metal tellurides include Kirkland Lake and Red Lake in Ontario (Precambrian); Brad and Nagyág, Romania (Transylvania) (Tertiary); Kalgoorlie in Western Australia (Precambrian); Vatukoula, Fiji Islands (Tertiary); and Cripple Creek in Colorado (Tertiary). The commonest silver tellurides in gold deposits are hessite, petzite, empressite, stuetzite and muthmannite in about that order. The various platinoid tellurides, including vincentite, kotulskite, merenskyite, temagamite and michenerite do not seem to have been recorded in gold deposits, except in the Rand where michenerite, moncheite and geversite have been noted (Feather and Koen, 1975). The most common base metal tellurides in gold deposits are altaite, PbTe, tetradymite, Bi_2Te_2S, joseite, $Bi_3Te(Se,S)$, coloradoite, HgTe, wehrlite, BiTe, hedleyite, Bi_7Te_3, and melonite, $NiTe_2$, in about that order. Frohbergite, $FeTe_2$, occurs in some of the veins of Sacaramb and Fata Baii in Romania (Ramdohr and Udubasa, 1973) and volynskite, $Ag(Bi,Sb)Te_2$, is present in the ores of the Zhana-Tyube goldfield in northern Kazakhstan (Spiridonov *et al.,* 1974). Tellurbismuth, Bi_2Te_3, often containing appreciable contents of antimony, has been recorded in a number of different types of auriferous deposits. Tellurantimony, Sb_2Te_3, is apparently rare in auriferous deposits.

Tellurides in skarn-type and gold-quartz deposits are invariably late minerals in the depositional sequence. In a number of auriferous deposits the tellurides are often closely associated with galena. Native gold and gold tellurides are commonly deposited contemporaneously, alternatively or clearly later than the base metal tellurides in most deposits. In others free gold and auriferous tellurides occur in association with the base metal tellurides but not in contact, and no particular paragenetic relationships can be established. At Cripple Creek, Colorado, the paragenesis of the mainly microscopic tellurides with respect to pyrite, galena, sphalerite, quartz and fluorite is complicated, but broadly speaking the tellurides are late (Lindgren and Ransome, 1906). In the Robb-Montbray gold property in Quebec, Thomson (1928) found the following genetic succession of sulphides and tellurides: pyrite, chalcopyrite and pyrrhotite, sphalerite, krennerite, tetradymite and altaite, petzite and coloradoite, native gold and chalcocite (supergene?). In the Kirkland Lake gold ores Thomson (1922) established the depositional sequence of minerals as follows: (1) quartz and pyrite; (2) carbonate stringers; (3) sphalerite followed in turn by chalcopyrite, tellurides and native gold. Thomson remarks repeatedly about the association of tellurides in the Ontario deposits with native gold, predominately in small late fissures and fractures in quartz and early sulphides. In the complex seleniferous gold ores of Salida, Indonesia the tellurides (hessite, sylvanite, petzite, altaite) are invariably associated with galena, which in the paragenesis of the deposits follows sphalerite, chalcopyrite and pyrite (Kieft and Oen, 1973). There are apparently no selenides in the deposit, the selenium being mainly in acanthite, galena and arsenpolybasite; hence, the paragenetic relationships of tellurides and selenides could not be determined. The general antipathy of telluride and selenide minerals in deposits has already been discussed in Chapter II.

The general distribution and habit of hypogene tellurides in auriferous deposits are of interest. Gold tellurides occur with greatest frequency in Tertiary deposits and in Precambrian deposits, mainly those of Archean age. Gold-quartz veins and polymetallic deposits, marked by the presence of quartz or extensive silicified zones, tend to be richer in auriferous tellurides than skarn deposits; the auriferous quartz-pebble conglomerates are notably poor in auriferous, argentiferous and base metal tellurides. In Precambrian deposits auriferous and argentiferous tellurides are generally accompanied by those of Hg, Pb, Cu and Bi; native tellurium is relatively rare in both Archean and Proterozoic deposits. Calaverite commonly predominates in Precambrian deposits, the other Au-Ag tellurides being subordinate. In Tertiary deposits tellurides of metals other than gold and silver are comparatively rare; native tellurium on the other hand is relatively abundant in some deposits. Krennerite tends to dominate over calaverite in a number of Tertiary deposits, but in some calaverite is the principle telluride. Native gold is commonly much more abundant in telluriferous Precambrian deposits (e.g., Kirkland Lake) than in most Tertiary deposits rich in tellurides (e.g., Cripple Creek). (*See also* the discussion on tellurides in Chapter II.)

Supergene tellurides appear to be relatively rare in auriferous deposits, although in the Central City district of Colorado some of the copper tellurides may be of this origin (Kelly and Goddard, 1969).

Some of the base meal tellurides accompany native gold and gold tellurides in certain recent placers but generally only in small amounts.

The *selenide* minerals, including naumannite, Ag_2Se, umangite, Cu_3Se_2, berzelianite, Cu_2Se, clausthalite, PbSe, aguilarite, $Ag_4(S,Se)$, penroseite, $(Ni,Cu)Se_2$, crookesite, $(Cu,Tl,Ag)_2Se$, guanajuatite, Bi_2Se_3, and tiemannite, HgSe, occur mainly in Tertiary gold-quartz veins. Examples are found at Republic, Washington; Tonopah, Nevada; Kushikino Mine, southern Kyushu, Japan; Radjang-Lebong, Sumatra, Indonesia; and the Hauraki belt (Waihi Mine) in New Zealand.

The Tennant Creek auriferous magnetite ores in Northern Territory, Australia are in Proterozoic rocks. They carry about 0.05 per cent selenium mainly partitioned into the new bismuth sulphosalt, junoite, $Bi_8Pb_3Cu_2(S,Se)_{16}$, wittite and heyrovskite, two other seleniferous bismuth-bearing, sulphosalts and a variety of other selenium-bearing sulphosalts (Large and Mumme, 1975). The galena in this deposit is also seleniferous containing up to 7.2 per cent Se.

Two facts about selenium in gold deposits are of interest: firstly, the element is a common trace element in the various sulphides and sulphosalts in nearly all types and ages of gold deposits, but selenide minerals appear only in abundance in deposits of Mesozoic-Cenozoic vintage; secondly, as mentioned above, tellurides and selenides are seldom associated with one another in gold deposits. The reason for this is obscure.

Sulphosalts are common in most types of gold deposits with the exception of the skarn type in which they are rare. *Tetrahedrite-tennantite* is probably the most abundant of the sulphosalts in gold deposits, occuring in veins and polymetallic lodes of all ages. The copper and lead sulphosalts such as *zinkenite, chalcostibite, jamesonite, cosalite, kobellite, semseyite, boulangerite, bournonite, meneghinite* and *jordanite* are most abundant in Precambrian, Paleozoic and Mesozoic deposits. They are relatively rare in Tertiary deposits. The silver sulphosalts, *proustite, pyrargyrite, matildite, miargyrite, smithite, stephanite* and *polybasite,* are uncommon in Precambrian deposits; they appear in increasing amounts in Paleozoic and Mesozoic deposits and reach their highest abundance and frequency in Tertiary deposits. There are some exceptions to this generalization. The Berens River deposit in northwestern Ontario for instance contained relatively abundant amounts of ruby silvers. In the Rand ores only tennantite-tetrahedrite, prousite and an unnamed $Ni_9Sb_2S_8$ phase have been identified (Saager, 1968; Feather and Koen, 1975). Several sulphosalt minerals are reported by Radtke *et al.* (1972*a*) in the disseminated ores at Carlin, Nevada.

The tin sulphosalts, *stannite,* Cu_2FeSnS_4, and *canfieldite,* Ag_8SnS_6, are restricted mainly to gold deposits in stanniferous regions.

Enargite, Cu_3AsS_4, and *famatinite,* Cu_3SbS_4, are particularly characteristic of deposits of Tertiary age. Locally they may appear in older deposits but rarely in any quantity; these minerals are very rare in Precambrian deposits. In the deposits located in the 'great circle of fire' that encompasses the Pacific, enargite is common in gold-bearing cupriferous polymetallic deposits. Here we may note its occurrence in many deposits in Chile, Peru, Argentina, western United States (particularly Butte, Tintic and Goldfield), Japan and the Phillipines (Luzon). In the siliceous gold ores of the Kasuga Mine in southern Kysushu, Japan, enargite, famatinite (luzonite) and native gold are the main ore minerals (Taneda and Mukaiyama, 1970). In the other great 'belt of fire' of the globe – the Mediterranean-Himalayan – enargite occurs in a number of auriferous deposits, but particularly in the quartz-sulphide ores at Bor, Yugoslavia.

Some of the sulphosalts in auriferous deposits, particularly tetrahedrite-tennantite, enargite and famatinite, commonly follow sphalerite and are more or less coeval with chalcopyrite in the paragenetic sequence of the veins. In these cases the minerals preceded the deposition of native gold and tellurides. Gold, however, accompanied the mineralization by tetrahedrite-tennantite in a number of deposits since these sulphosalts contain the precious metal as lattice constituents.

The remainder of the sulphosalts, including in places tetrahedrite-tennantite, are late minerals in most gold deposits, introduced at about the same time as gold. At Yellowknife, native gold and various sulphosalts are intimately associated, the latter being particularly good indicators of high grade shoots. A similar situation exists in all other gold deposits seen by the writer. Under the microscope the sulphosalts are commonly closely associated with gold in its ores, both forming mutual boundaries in many cases. In some sections one often sees gold apparently replacing the sulphosalts, and gold and sulphosalts often occur together in late veinlets with quartz and carbonates (Pl. 14). In banded and crustified ores the sulphosalts and gold are generally always intimately associated, sometimes alternating in their depositional sequence. In vugs and nests, gold crystals and dendrites can sometimes be seen perched on crystals and fibres of sulphosalts. Some of the gold in shoots containing sulphosalts is present as a lattice constituent of these minerals, particularly tetrahedrite-tennantite. Tiny grains of gold with no apparent orientation are also commonly present in sulphosalts. These may have been exsolved from the minerals, or may have been coprecipitated with them.

The rich silver-bearing sulphosalts, including pyargyrite, proustite and polybasite, commonly precede the deposition of native gold in most deposits, although in some the minerals commonly look to be coeval.

Gold tellurides apparently bear the same relationships to the sulphosalts as native gold, but I have rarely seen these two types of minerals in juxtaposition where unequivocal paragenetic conclusions could be drawn. One often sees, however, gold tellurides in very late veinlets and as projecting crystals in the latest vugs in gold veins. These are usually later than the sulphosalts. In the complex seleniferous gold ores of Salida, Indonesia, pearceite, polybasite, prousite, enargite (luzonite) and arsenpolybasite apparently followed the deposition of tellurides (Kieft and Oen, 1973). (For the relationship of aurostibite to sulphosalts *see* the discussion above under stibnite and the section on aurostibite in Chapter II.)

Supergene sulphosalts appear to be rare in auriferous deposits. In the writer's experience only the ruby silvers may occur as supergene minerals. In the zones of reduction of some auriferous deposits in Yukon pyrargyite is present but is very low in gold content (Boyle, 1965*a*). The relationships to supergene gold could not be determined.

Hematite, magnetite, ilmenite, franklinite, spinel and *gahnite* have all been recorded from gold deposits. Most of these minerals are relatively minor gangue constituents in gold-quartz and gold-bearing polymetallic deposits, but in some skarn and pipelike deposits they may be relatively abundant. In some skarns magnetite is a concentrator of gold together with arsenopyrite and chalcopyrite. Hematite occurs in deposits of all types and ages. The mineral is particularly abundant in the Tarkwa quartz-pebble conglomerates of Ghana. There, it occurs abundantly in the matrix and forms thin (sedimentary) layers in the conglomerate beds. In gold-quartz veins a dusting and impregnation by hematite is common in some districts, examples being Kirkland Lake, Ontario and Tennant Creek, Australia. Specular hematite also occurs in some of the veins at Kirkland Lake. At Tennant Creek, gold, bismuth and copper mineralization occurs in discordant magnetite- and hematite-rich lodes which have an ellipsoidal to pipelike shape (Large, 1974). These pipes cut felsic sediments and pyroclastics of Lower Proterozoic age. Massive magnetite and much chlorite form the core of the Juno lode, and gold is concentrated in the centre of this core. The other elements are vertically zoned.

Auriferous uranium deposits are commonly marked by hematitization, which consists of a pervasive reddening of the rock adjacent to the quartz-carbonate and pitchblende veins. The hematite appears in most cases to be locally derived by the oxidation of the ferrous iron in minerals such as amphiboles, pyroxenes and micas. Some ferric iron may be introduced into the sites of mineralization from sources in the nearby host rocks. Some auriferous uranium deposits have both intensely chloritized and hematitized zones that halo the mineralization sites. Such phenomena suggest introduction of both magnesium and iron, probably from relatively nearby rocks.

Kolosova and Onishchuk (1971) described gold deposits from eastern Transbaikal (Novinka, Magnitnyy and Ugol'noye in the Ust-Kara gold belt) that are rich in magnetite. The deposits are mainly magnetite veins and lodes in granitoids and various dykes and contain magnetite, hematite, actinolite and quartz with which the gold is for the most part associated. There are in addition a number of other minerals including bismuthite, tetradymite, chalcopyrite, arsenopyrite and very rare, isolated grains of marcasite, ilmenite, wolframite, galena, sphalerite, native bismuth, pyrrhotite and cobaltite. Feldspars occur often among the vein minerals, and tourmaline, chlorite, biotite, epidote and hornblende are found more rarely in the magnetite veins. Scheelite is present in relatively large amounts. Kolosova and Onishchuk state that part of the gold crystallized almost simultaneously with the magnetite; some gold was also precipitated before and after the iron oxide. Gold-bearing magnetite pebbles occur in the alluvium of a number of stream valleys in the area.

In Chile certain auriferous veins cutting granitic bodies are marked by an abundance of specularite and some contain magnetite (Ruiz and Ericksen, 1962).

Magnetite and ilmenite are rare in Tertiary deposits, and franklinite and gahnite are particularly rare in all deposits. In most of the quartz-pebble conglomerate ores (e.g., Rand and Jacobina) magnetite and ilmenite are rare. Geologists, who favour a placer origin for these deposits, maintain that this is because these minerals have been sulphidized and now appear mainly as pyrite.

Where relationships can be established gold and gold tellurides are generally later minerals than magnetite, ilmenite, hematite, franklinite and gahnite. In some deposits, however, hematite is a very late mineral, often related to a mineralization quite unrelated to the gold period. Such a situation occurs in places at Yellowknife where late faults cut the gold orebodies. Occasionally in some deposits one also sees veinlets of magnetite much later than the gold mineralization.

There are no particular indicator qualities of any of the iron and zinc oxide minerals for gold in any type of deposit as far as the writer can ascertain.

Hematite, magnetite, ilmenite, spinel and chromite are commonly encountered in auriferous placers, the first four minerals in various geological terranes and the last where ultrabasic bodies are a feature.

Corundum is an uncommon mineral in gold deposits. It may occur in the wall-rock alteration zones of certain auriferous quartz veins in highly aluminous rocks such as schists, gneisses, syenites, etc. Gem sapphires and rubies are commonly encountered in gold placers as in New South Wales; in the gold washings near Helena, Montana; and in the concentrates from Eldorado Bar on the Missouri River (sapphires); and elsewhere.

Rutile and *leucoxene* commonly occur as accessory minerals in gold deposits particularly those in basic rocks. Studies of the distribution of rutile and leucoxene in the Yellowknife deposits in greenstones (Boyle, 1961*a*) indicate that the minerals are formed mainly as a result of the carbonatization and sericitization of basic rocks. The titanium cannot be accommodated in any of the alteration minerals formed in the wall-rock alteration zones and veins and hence appears as rutile and/or leucoxene. This phenomena is discussed further in the section on alteration processes in this chapter.

Rutile and leucoxene are relatively common in the ores of the Witwatersrand. According to Ramdohr (1953*b*) and Liebenberg (1955) the rutile (and leucoxene) formed from titanium liberated during pyritization of black sand.

Rutile, brookite, anatase and leucoxene are common in recent gold placers.

Cassiterite and other tin minerals are relatively uncommon in most gold deposits, but in some mineral belts they (mainly cassiterite) are present. Examples are found in the stanniferous regions of the northeastern and eastern U.S.S.R. (Nekrasov, I. Ya., 1973; Radkevich *et al.,* 1965; Radkevich, 1969); in some of the auriferous deposits of the western U.S.A. as at Marysvale, Utah (Radtke *et al.,* 1967); in Bolivia, Malaya, New South Wales, Australia; and elsewhere. In most of these occurrences cassiterite is paragenetically older than native gold and other gold minerals.

Small amounts of apparently detrital cassiterite are present in some of the reefs of the Rand (Liebenberg, 1955), but in general the tin content of quartz-pebble conglomerates is very low (Table 35).

Cassiterite may accompany gold in certain recent placers.

The oxides and hydrous oxides of iron and manganese, mainly *limonite* and *wad,* are abundantly developed in the oxidized zones of most auriferous deposits. Their formation is examined in detail in Chapter IV.

Scheelite and *wolframite* are common minerals in gold deposits of various types mainly the skarn, gold-quartz and polymetallic type. Tungsten is present in only trace amounts in the Witwatersrand and other quartz-pebble conglomerates (Table 35). Scheelite and wolframite have not been recorded in the Rand ores (Liebenberg, 1955; Saager, 1968; Feather and Koen, 1975) – a fact which seems peculiar considering that the deposits are supposed to be modified placers, and that gold, especially that derived from Precambrian terranes, is usually accompanied by tungsten (scheelite).

Scheelite has a rather erratic distribution both locally and regionally in auriferous deposits. The mineral occurs in deposits of all ages from Precambrian to Tertiary, and there is seemingly no differnce in the abundance of the mineral with time. Some gold belts, however, are notable for their scheelite whereas others have little or none of the mineral. In the Porcupine (Timmins) district of Ontario for instance scheelite is rather common in the gold veins, whereas in the Kirkland Lake area the mineral is very sparse, although small amounts do occur in the Chesterville and Kerr Addison mines.

Wolframite is actually a rather rare mineral in gold deposits of all types. I have seen it in only two places (Outpost Island and Matthews Lake area, Northwest Territories) in Precambrian gold deposits and not at all in deposits of Paleozoic and Mesozoic age in Canada. Curiously enough, wolframite (hüberite) appears in very small amounts in some Tertiary deposits, particularly in those at Tonapah, Nevada and Cripple Creek, Colorado; also in some deposits in the far eastern U.S.S.R.

Scheelite is generally an early mineral in gold-quartz veins. Frequently it is fractured and seamed by late quartz veinlets carrying gold and gold tellurides. Some shoots in gold-quartz veins enriched in scheelite tend to be relatively low grade in gold. In the Meguma Group of Nova Scotia this seems to be due to the fact that some of the scheelite-rich veins appear to be younger than the gold veins.

Both scheelite and wolframite may accompany gold in recent placers.

Uranium and *thorium minerals* are relatively rare in most gold deposits throughout the world. In the Witwatersrand and other quartz-pebble conglomerates, however, they are ubiquitous and economic minerals. Gold-quartz veins, auriferous skarns and some auriferous polymetallic deposits in uraniferous provinces also carry uranium and thorium minerals in some districts. Examples are found in the Uranium City area of Saskatchewan; in the Chihuahua district, Mexico (Krieger, 1932); in the Central City district of Colorado (Sims *et al.,* 1963); in the Alligator rivers region, Northern Territory, Australia; in the Mitterberg district of Austria (Bauer and Schermann, 1971; Siegl, 1972; Paar, 1976); and in the Eldorado area of Ontario.

Detailed studies of the uranium minerals and their relationship to gold in the Witwatersrand bankets have been made by Liebenberg (1955), Ramdohr (1958*a,b*) and Feather and Koen (1975). The principal uranium species are uraninite and uraninite-bearing hydrocarbon (thucholite). Some of the uraninite is said to be detrital and some secondary or redistributed. The thucholite is interpreted as consisting of remnants of detrital uraninite replaced to varying degrees during thucholitization; some secondary uraninite may accompany the detrital grains in the thucholite. Gold is intimately associated with the uranium minerals, and there is a general sympathetic relationship between the uranium and gold contents, a feature also emphasized by Von Rahden and Urli (1969) who state:

At all three mines, the gold was found to occur in at least two generations. The older generation occurs in the form of small, generally rounded inclusions, totally enclosed within pyrite grains that show no evidence of healed cracks that could originally have permitted the entry of the gold. The second and younger generation of gold constitutes the major portion of the gold seen in polished sections. This younger gold occurs as stringer-like inclusions embedded in phyllosilicates as anhedral growths replacing pyrrhotite, pyrite, chalcopyrite and uraninite, and occasionally as small euhedral crystals showing bright facets and embedded in phyllosilicates or occurring within cracks in quartz grains. This second generation of gold has been described in considerable detail by Liebenberg, Von Rahden, and Schidlowski. These investigators attributed the form shown by this second generation of gold to the effects of dynamic and localized metamorphism of the conglomerates, when remobilization and recrystallization of the gold occurred. They postulated that it was during this period of remobilization of the gold that the uraninite and sulphides were replaced by gold. The movement of the gold did not exceed perhaps a few millimetres, and was not sufficient to upset or affect the original sedimentary distribution pattern to any significant extent.

The relationships of gold and uranium minerals in the Box Mine at Goldfields, Saskatchewan are not entirely clear. It would appear that the uranium minerals are later than the gold mineralization and that the two suites may be independent of each other. The same may also be true at the Nicholson Mine in the same area, although in some samples from this mine the gold, often containing high amounts of platinoids, occurs in calcite that veins and cements the pitchblende. In different samples from this deposit and in other deposits in the Goldfields area gold occurs as small inclusions in the pitchblende. Some of this gold appears to be late, although this observation is tenuous.

In the pyritic uraninite-gold-quartz veins in altered porphyries in the Chihuahua district in Mexico, the gold is paragenetically later than the uraninite occurring in fractures in the uraniferous mineral (Krieger, 1932). Samples from the Jabiluka deposits in the Alligator rivers region, Northern Territory, Australia show that the native gold and associated tellurides, including altaite and melonite, are later than pitchblende and uraninite in the paragenetic sequence.

At the Richardson Mine at Eldorado in eastern Ontario (Boyle and Steacy, 1973; Steacy *et al.*, 1973, 1974*a*,*b*), some of the native gold occurs in clots of thucholite, giving the impression that the gold exsolved from an organometallic gel. In the same mine native gold occurs in fractures in *brannerite.* Brannerite has also been noted in other gold and silver mines, notable at Bou Azzer (Jouravsky, 1952*b*), Plumas County, California (Pabst and Stinson, 1960) and La Gardette (Isère), France (Geffroy, 1963). At the Plumas County occurrence the gold is clearly later than the bannerite. In the La Gardette deposit the paragenesis is as follows: brannerite-quartz-native gold-galena-barite. Brannerite also occurs with uraninite in the veins of Mitterberg, Salzburg (Austria). Gold is an associated mineral and is later than brannerite and uraninite (Siegl, 1972). Brannerite is a constituent of some of the ores of the Rand, particularly the Vaal Reef (Feather and Koen, 1975). Its relationship with gold is not stated.

Excepting the Rand[23] and some deposits in the Lake Athabasca[23] region of Saskatchewan, uranium and thorium minerals are particularly rare or absent in deposits of Archean age. The reason for this is a problem in metallogenesis which remains unsolved.

Chromite is rarely encountered in auriferous deposits of the skarn, gold-quartz or polymetallic type. As rounded to euhedral grains the mineral is widely distributed in the reefs of the Witwatersrand but only in trace and minor amounts (Feather and Koen, 1975). It exhibits a closely sympathetic relation with zircon, and is generally considered by most investigators to be of detrital origin.

Chromite is a heavy mineral constituent of numerous recent gold placers, particularly those in terranes marked by the presence of ultrabasic-basic rock suites and Ni-Cu sulphide deposits.

Platinoid minerals constitute a number of natural alloys and a series of compounds with S, As, Sb, Bi, Te, Pb and Sn. The platinoid alloys and their association with gold have been mentioned in the first part of this section. The other platinoid compounds are relatively rare constituents of gold deposits especially the gold-quartz type. Certain auriferous skarn deposits associated with basic and ultrabasic rocks, or in calcareous rocks with associated serpentinites, may carry platinoid minerals, principally sperrylite, cooperite and stibiopalladinite. Deposits of this nature are known in South Africa and in Sumatra, Indonesia. Various auriferous polymetallic veins, rich in copper minerals, may carry minor amounts of platinoid minerals, principally sperrylite. The Cuniptau Mine at Goward, Ontario is an example of this type of deposit, others are known in the United States, Colombia and U.S.S.R. Without exception these deposits are either in or closely associated with ultrabasic-basic stocks, plugs or dykes. Certain unusual quartz veins and pegmatites in various parts of the world carry small amounts of platinoid minerals and traces of gold. Such veins occur in Colombia, U.S.S.R., South Africa, New Zealand and Ontario. The platinoid minerals are commonly associated with pyrite, specularite, chrome chlorite and sericite. Most of these veins occur in or near igneous ultrabasic-basic rocks. Certain gold-bearing uraniferous veins and others greatly enriched in selenium may contain small amounts of platinoids. The first is exemplified by the Nicholson Mine in the Beaverlodge area of Saskatchewan, the second by veins at Tilkerode, Harz, Germany and the Artonville Mine, Messina, South Africa.

The reefs of the Witwatersrand contain very minor amounts of platinoid minerals comprising various alloys, which have been previously described, and other compounds (Feather and Koen, 1975). The alloys are generally always associated with a number of platinoid sulphides, arsenides, antimonides and tellurides including sperrylite, hollingworthite, iridarsenite, ruthenarsenite, geversite, michenerite, moncheite, laurite, braggite, cooperite, a palladium telluride and an unnamed mineral with composition RhS_2. Feather and Koen (1975) consider the platinoid alloys to be essentially of detrital origin, modified subsequently by coatings and overgrowths of the secondary platinoid sulphides, arsenides, etc. Few of the

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[23] The age of the Witwatersrand is uncertain; it may be Archean, although its stratigraphic position and other features suggest that it is of Lower Proterozoic age. The gold-uranium deposits of the Lake Athabasca region may be partly Archean in age. However, some of the uranium deposits cut Proterozoic rocks (Martin Formation), and age dating by Pb/U and Pb/Pb methods indicates that the uranium minerals have apparent ages ranging from 190 to 1850 m.y. (Robinson, 1955).

platinoid minerals of the Rand have been observed in polished sections, and hence their relationship to the gold is not known. The electron probe analyses of some of the platinoid minerals of the Rand indicate very low gold contents.

Platinoid minerals accompany gold in recent placers, particularly in terranes containing igneous ultrabasic-basic bodies and Ni-Cu sulphide deposits. Most of the platinoid minerals are alloys of the various elements, but sperrylite, arsenopalladinite, mertieite and numerous other platinoid compounds have been recorded from auriferous placers.

> In every species of gold there is a proportion of silver; in some one-tenth part, in others a ninth, and in others an eighth.
>
> —Pliny the Elder, 79 A.D.

Au/Ag ratios of auriferous deposits

The Au/Ag ratios of various types of gold deposits, especially with respect to metallogenic provinces and epochs, is a fascinating problem, but one that has received relatively little detailed research. In what follows the more recent significant papers dealing with Au/Ag ratios in gold deposits are reviewed, and some general conclusions are drawn from these and the writer's own research.

A clear distinction should be made between fineness of gold and the gold-silver ratio of deposits. The latter refers to the total gold and silver in the deposits as determined by analyses (assays) of the ores expressed as the ratio Au/Ag; the former is calculated in parts per thousand and refers to the proportion of gold present in the naturally occurring metal in the deposits. In general the minor element in native gold is mainly silver, but other base and precious metals may also occur, e.g., Cu, Fe, Pt metals. (*See also* the section on native gold in Chapter II.) Where the amount of base metals is high in the native gold or bullion the ratio (Au/Au + Ag) × 1000 or the *true fineness* should be used as suggested by Fisher (1945).

In the discussion that follows emphasis is placed on the Au/Ag ratio of deposits. Where appropriate, remarks will be made about the fineness of native gold in deposits. Before proceeding it should be noted that some of the investigations described in the literature are based on the fineness of bullion, which may not be an accurate measure of the Au/Ag ratio in deposits because the percentage recovery of the two precious metals from the ores is seldom stated. Where the quantity of argentiferous minerals is minimal in deposits the fineness of the bullion is a good estimate of the Au/Ag ratio; where argentiferous minerals are abundant the bullion results pertaining to the Au/Ag ratio of the deposits may be seriously in error since gravity and cyanide methods do not generally remove all of the silver from such minerals. Sharwood (1911*c*) has discussed some of the effects that metallurgical practise has on the Au/Ag ratio in bullion. His conclusions are valid to this day.

Pryor (1923–1924) studied the bullion assays of the Kolar goldfield, India. In addition to noting some differences in the fineness of the bullion from the different mines he found a general increase in the Au/Ag ratio of the bullion with depth in the deposits (surface fineness, 890; at depth, 930). He attributed this to thermal effects, the ores at depth being deposited at a higher temperature than those near the surface. This indicates a higher mobility for silver than gold, a feature that has been repeatedly emphasized for many years, and one that has some chemical support.

In the precious metal deposits of the western United States, Nolan (1933) observed that the Au/Ag ratios varied within wide limits. In some of the mines in the Silver City–De Lamar region the ratio is less than 1:100, but in a number of other camps it is almost 1:1. Nolan thought that the ratios were perhaps related to the temperature of deposition since he found an Au/Ag ratio of 1:105 in the (hot) central focus of mineralization whereas the ores more distant from the central focus, in the cooler zones, have a ratio of about 1:95. He also mentioned the fact that at Oatman, Arizona successive stages in the vein formation, five in number, have a progressively larger proportion of gold. Addie (1964) in a more recent paper, likewise, thought that Au/Ag ratios are a sensitive geothermometer. He interpreted the Au/Ag ratio to be an expression of exsolution of a gold-silver solid solution as the temperature changes. Thus, he maintained that high Au/Ag ratios represented higher temperatures and low Au/Ag ratios lower temperatures. A deposit that shows an increase in the Au/Ag ratio with depth would, therefore, indicate that the thermal source was being approached. Such a simplification seems too general in view of the data presented by Bruce mentioned below, although it agrees as noted above, with the chemical fact that silver is more mobile than gold.

Bruce (1943) investigated the Au/Ag ratios of the bullion from certain Ontario gold mines (Porcupine, Kirkland Lake, Malartic) and concluded that: (1) the Au/Ag ratio for some deposits seems to decrease with depth; (2) the ratio is different for different kinds of wall rocks even on the same mine level; and (3) silver shows less variation than gold.

Thomson *et al*, (1950) and Charlewood (1964) gave average Au/Ag ratios based on production figures for most of the gold mines along the main ore zone at Kirkland Lake. These range from 3.9 to 8.9 despite the fact that the ores are relatively uniform as regards their mineralogy. The average fineness of the bullion ranged from 798 to 899. The ratio Au/Ag, calculated by the writer from the yearly production figures, shows an erratic behaviour. In some mines the ratio decreases with time and in others an increase or erratic behaviour is evident. Whether these ratios can be keyed to depth is a question since there is seldom an orderly production depthwise with passing years in gold mines.

In the publication by Thomson *et al.* (1950) noted above, Hopkins discussed the Au/Ag ratios based on the annual production of the Wright-Hargreaves Mine. He noted that the Au/Ag ratio decreases with depth and remarked that this is due to an increase in the silver content rather than a decrease in the gold content. Hence, the trend in the Au/Ag ratio does not help to predict the depth at which the precious metal content will be below ore grade.

Mills (1954) studied bullion assays and mine production records finding a systematic variation in the purity of the gold recovered during the years 1936 to 1946 in the O'Brien Gold Mine, Kewagama, Quebec. From 500 to 1200 ft beneath the surface the ratio (Au/Au + Ag) × 1000 increased from 860 to 920; below 1200 ft the ratio was constant at an average value of 925. Between the surface and 500 ft the ratio was unexpectedly high (900–910); this was interpreted as possibly due to secondary enrichment. Mills also found that the proportion of gold recovered by cyanidation as against that recovered by amalgamation during 1939–1946 increased continuously suggesting that the particle size became smaller with depth.

Shcherbina (1956*a*) has given a number of Au/Ag ratios of various deposits throughout the world and drawn a few conclusions that merit repeating here. He found that:

1. Gold enrichment (a high Au/Ag ratio) is present mostly in higher temperature and deeper-seated ore deposits, whereas silver enrichment (a low Au/Ag ratio) is characteristic of low temperature ore deposits formed at intermediate depths or near the surface. This is correlative with the vapour pressures of the elements, viz. silver has a higher vapour pressure than gold at temperatures above 700°C. Silver is, therefore, more volatile than gold and hence migrates farther from the source of heat (magma) and tends to be enriched near the surface.
2. Deposits in older geological formations are frequently richer in gold (a high Au/Ag ratio), whereas in younger formations silver is more abundant (a low Au/Ag ratio).
3. Ore deposits formed by more alkaline hydrothermal solutions, as witnessed by the alteration of the wall rocks, are richer in gold, whereas those formed by weaker alkaline solutions are richer in silver. This circumstance is explained as due to the different modes of gold and silver in alkali sulphide solutions. Thus, silver is carried mainly as AgHS, whereas gold is transferred in the form of $[AuS_3]^{3-}$ and $[AuS_2]^{-}$ ions.
4. Gold is predominant in telluride ores, whereas silver is generally dominant in selenide ores. An analogous, but not a strict, relationship is observable with respect to As and Sb. Thus, gold prefers the arsenopyrite or smaltite mineral association, whereas silver favours antimony assemblages.
5. The Au/Ag ratio depends on regional metallogenic peculiarities, being low for the Circum-Pacific belt of America and high for the countries bordering the Pacific Ocean on the southwest.
6. During near-surface processes silver is much more mobile than gold.

Badalov and Badalova (1967) investigated the regularities of the distribution of gold and silver in the principle sulphide ore minerals of two different metallogenic provinces (Karamazar and western Uzbekistan) in U.S.S.R. Briefly their conclusions were:

1. The distribution of gold and silver in the sulphides of the various ore deposits depends on the content of sulphides, sequence of their deposition and the affinity of the two precious metals for certain ore minerals. Different minerals serve as concentrators and carriers of gold and silver depending on the character of ore-bearing generations, geochemical province and genetic type of ore deposit.
2. As a rule, the content of gold in the sulphides decreases from the older to the younger generations, while the content of silver increases.
3. The Au/Ag ratio in the ore minerals is characteristic of a given mineralization. In the Karamazar region the maximum ratio between the average contents of gold and silver is 1:28, while in the western Uzbekistan deposits it reaches 1:1, and even 2:1. Together with the fineness of gold, the Au/Ag ratio may be used in deciphering the geochemistry and genesis of the ores.
4. The sharp difference in the assemblage of ore-bearing generations and in the distribution of gold and silver in the sulphides of the Karamazar and western Uzbekistan mineralized zones may be explained by the difference in the role of the enclosing rocks during ore deposition. In western Uzbekistan, these rocks are sandstones and shales; in the Karamazar region, they are igneous rocks.
5. Investigation of the distribution of gold and silver in the endogene orebodies of a given region may be helpful in predicting the presence of gold deposits proper. Certain quantitative relationships have been established in the Karamazar region between the various gold-free but silver-rich sulphide deposits and the gold deposits of comparable size.

Fitzgerald *et al.* (1967*a,b*) examined the feasibility of using Au/Ag ratios in solving a fault displacement problem in the Bourlamaque district of Quebec (Lamaque and Sigma mines). The ore zones in these two mines are composed of a multiplicity of gold-bearing quartz veins extending vertically to depths greater than 4000 ft. The mines are about 2500 ft apart horizontally, and are separated by a steep-dipping fault zone. The investigators noted that the Au/Ag ratios at both Lamaque and Sigma, calculated from annual mint (bullion) returns over the past 30 years, represent very large samples. These values, when plotted against the annual mean depth of mining, were found to increase with depth in both mines at about the same rate, with Lamaque having the higher values. If it is assumed that both orebodies formed under similar conditions, the higher Au/Ag ratios found at Lamaque suggest that this orebody has been raised approximately 1300 ft with respect to Sigma by postore movement on the fault zone. Stope samples taken over a vertical range of 2285 ft at Lamaque were analyzed for Au and Ag by two independent methods. The Au/Ag ratios determined by conventional analysis (i.e., Au by fire assay; Ag by atomic absorption) were variable, but were in the same range as the ratios from the mint (bullion) returns. The investigators found no evidence that intrastope variations are caused by such geological features as the composition of the wall rock or the thickness or grade of the vein. The Au/Ag ratios obtained by electron probe microanalysis of gold grains taken from the stope samples were approximately three times higher than the ratios obtained by conventional analysis, and there appeared to be no change in gold fineness with depth. These results suggested to the investigators that both the intrastope variations and the increase in the Au/Ag values with depth are caused by the presence or absence of Au- and Ag-bearing minerals other than the native alloy. Silver was found to occur in petzite (25% Au, 42% Ag) and tetrahedrite (12% Ag), but these minerals are rare in the mines and could not adequately account for all the missing silver. Pyrite is the most common sulphide, making up about 2.5 per cent of the ore; it contains about 2.3 oz of silver per ton of pyrite, which is sufficient, it was thought, to account for the difference in silver content obtained from native gold and silver recovered either from individual stope samples or from the mill as reported in mint returns.

In the Balei ore field, U.S.S.R., (*see also* below) Gapontsev and Polikarpochkin (1969) observed significant differences in the Au/Ag ratios in various parts of the gold veins and their primary dispersion halos. Above the economic ore shoots the Au/Ag ratios ranged between 0.5 to 1.0; in the ore shoots the range was 1.25 to 5.0; below the ore shoots the range was 0.14 to 0.33, and in the peripheral parts of the primary halos the ratio fell to values as low as 0.02. To generalize, their results showed that there is both a lateral and vertical upward and downward increase in the Au/Ag ratios with proximity to ore. This is essentially the same as noted at Yellowknife (Table 48).

Fortin (1969) studied the distribution of gold and silver in the Sullivan orebody, Val d'Or, Abitibi-East County, Quebec. The orebody comprises auriferous quartz-tourmaline veins in the peripheral parts of the Bourlamaque batholith. Statistical studies showed the grade population to be bimodal, affected by an important particle (nugget) effect; each population was random. The Au/Ag ratio was found to increase systematically with depth in a linear manner.

Kitaev *et al.* (1970*c*) investigated in detail the Au/Ag ratio in the primary aureoles of the Balei goldfields in U.S.S.R. These deposits are veins with chalcedonic quartz and relatively few sulphides. The background content of gold in the country rocks is of the order of 0.001 ppm and silver 0.006 ppm. The Au/Ag ratio fluctuates in the vicinity of 0.166. In the halos the gold content ranges from 0.01 to 1 ppm or more; the respective silver values are 3 to 6 ppm. On the dip the Au/Ag ratio follows the curve shown in Figure 8; across the strike the generalized situation is as shown in the right-hand part of the figure. The investigators concluded that a study of the silver-gold ratio could provide information on the paths of movement of hydrothermal solutions and details of the microstructure of aureoles. In addition, the ratio has considerable applied significance for the determination of the location of the zone of optimum mineralization and the level of erosion of the orebodies; and a comparative estimation of the degree of gold mineralization in the various orebodies.

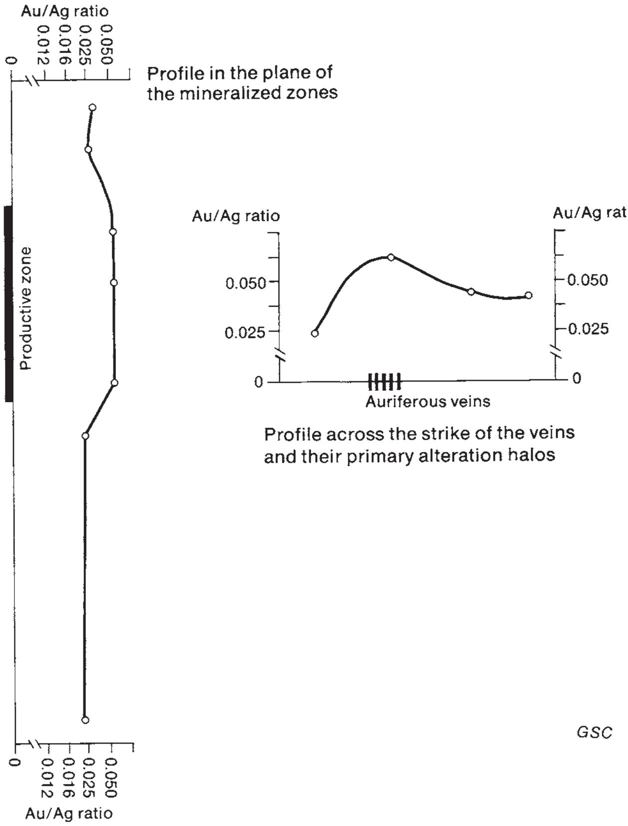


Figure 8. Generalized profiles of the Au/Ag ratio in the Balei goldfield, eastern Transbaikal, U.S.S.R. (after Kitaev *et al.*, 1970*c*).

Koroleva (1971) examined the Au/Ag ratios in the endogene gold-bearing deposits of middle Asia, U.S.S.R., which can be categorized as: (1) gold-pyrite-arsenopyrite-pyrrhotite-telluride deposits; (2) mixed polymetallic deposits containing gold and silver; and (3) polymetallic deposits containing admixed gold. Her conclusions are as follows:

1. The Au/Ag ratio decreases from the oldest mineral associations to the youngest. In all deposits the sulphide associations composed of minerals of iron, arsenic and copper, crystallizing during the oldest stages of the hydrothermal process, are the richest in gold. Silver accumulates in the younger minerals of a given stage, or at the end of the depositional process.
2. In the gold and gold-bearing deposits the Au/Ag ratio is determined by the dominance of the mineral with which gold is associated. The highest ratios are characteristic of ores in which the arsenopyrite-pyrite association predominates. With increase in pyrite content the ratio decreases, reaching a minimum in ores with predominant galena and silver minerals.
3. The Au/Ag ratio may be used to predict the mineralogical composition of an association exploitable for gold in little known ore deposits.
4. In the gold and gold-bearing deposits of middle Asia the Au/Ag ratio is generally higher than in the deposits of Altai, Caucasus and Mexico. This indicates a greater concentration of gold in middle Asia. The Au/Ag ratio may be used in preliminary evaluation of individual deposits and prospects.
5. There is a relation between the fineness of gold and its occurence in a given mineral association. Widespread variations in the fineness of gold in some deposits is due to the presence of several mineral associations.

In the Byngov deposit in the central Urals where the mineral assemblage includes a variety of base and precious metal tellurides and native gold in quartz veins, Berzon and Bushlyakov (1971) found that the Au/Ag ratio decreased sharply with depth from 1.5 to 1.1. They also found that the presence of disseminated pyrite and chalcopyrite in the veins decreased both the gold and silver contents.

Forsythe (1971) noted a decrease in the Au/Ag ratio with depth in the main ore shoot of the Crown-Crescent lode in the Emperor Gold Mine, Fiji. He attributed this to vertical zoning of gold-silver tellurides. The zoning apparently resulted from a complicated two stage mineral deposition sequence of ore minerals and reactions of second stage solutions with minerals deposited during the first mineralization stage.

Saager and Bianconi (1971), using statistical methods, examined the Au/Ag ratios in the Mount Nansen gold-silver deposit, Yukon, Canada. This deposit consists of narrow steeply dipping veins in rocks ranging from Precambrian to

Tertiary. The primary mineralization is complex with pyrite, arsenopyrite, various sulphosalts, stibnite, galena and sphalerite. The deposit may be of Cretaceous–early Tertiary age. A general down-dip decrease in silver content and a fairly uniform gold distribution was found in one of the mines, resulting in a general increase in the Au/Ag ratio with depth.

Stephenson (1971) noted that the silver content (~0.04 oz/ton) of the San Antonio Gold Mine in the Rice Lake district of Manitoba remained relatively constant during the period 1935–1968, whereas the gold tenor of the ores declined from about 0.30 to 0.20 oz/ton during the same period. He correlated these values with depth and observed that the Au/Ag ratio decreased from about 7.1 to 5.1 over a depth of 5380 ft. His curve shows a significant high Au/Ag ratio equal to 8 near the surface suggesting some supergene enrichment of gold, a feature also noted by Mills (1954) as stated above.

Randall (1973) found a rather complicated pattern in the Anglo-Rouyn Cu-Ag-Au Mine at La Ronge, Saskatchewan. The Au/Ag ratio changed from 0.18 at the start to 0.28 near the end of operations. With time, the copper grade decreased, the gold grade increased and the Cu/Ag ratio was nearly constant. Electron microprobe studies of the concentrate showed most of the silver to be present in chalcopyrite. Only half the gold was found to be so associated, the rest being in iron sulphides, sphalerite and silicates. Gold-silver assays from ore samples gave ratios from 0.003 to 0.83. Samples rich in quartz, chlorite or iron sulphides showed higher Au/Ag ratios than those rich in chalcopyrite. Ore with a high proportion of chalcopyrite gave ratios of 0.06 to 0.1. Metal contents and ratios were found to be spatially distributed in the shallow, elongate, northeast-southeast trending orebody. The centre of the body shows banded chalcopyrite ore with few apparent metamorphic effects and a relatively low Au/Ag ratio. Higher Au/Ag ratios were found in quartz-rich, nonbanded ore toward the ends of the orebody where ralative proportions of chalcopyrite, pyrrhotite and pyrite vary, and metamorphism is more apparent. The irregular distribution of gold was thought to be due to original deposition with copper, later deposition or selective redistribution during metamorphism.

The pattern of the various precious metals in the chalcopyrite ores of the southern Urals (Magnitogorsk) is likewise complicated (Novgorodova, 1976). She found that the distribution of Pd, Pt, Au and Ag in pyrite, pyrrhotite, chalcopyrite and sphalerite does not obey the lognormal law. The Pd/Pt ratio varies uniformly with changes in the Au/Ag ratio; the Pd/Pt ratio increases and the Au/Ag ratio decreases from the early- to late-stage mineral assemblages.

Berman and Gorelyshev (1974) concluded from their study of the Au/Ag ratio of an auriferous deposit in the northeastern part of the U.S.S.R., that the ratio is the result of many geological influences but particularly the character of the mineral associations.

Hargraves (1963), Von Rahden (1965), Addie (1964) and Saager (1969) have investigated the Au/Ag ratio in the ores of the Witwatersrand. Their conclusions are discussed subsequently.

Ol'shevskiy (1975) studied the Au/Ag ratio in 71 near-surface (mainly Tertiary) gold-silver deposits in various parts of the world, 25 of the deposits being in the eastern part of the U.S.S.R. He noted a dependence of the ratio on the types of wall rocks in which the deposits occurred. In general in the deposits in U.S.S.R., those in acidic rocks (rhyolites, etc.) have a low Au/Ag ratio (<0.05) whereas those in intermediate rocks (andesites) have a high value (>0.05). Similar results were noted in other (mainly Tertiary) deposits in various parts of the world. Ol'shevskiy thinks that the relationship between the Au/Ag ratio and the composition of the host rocks can be explained by the fact that the gold-silver mineralization is connected paragenetically with the plutonic-volcanic rock complexes. The more acid volcanic rocks are formed at near-surface horizons and consequently since silver is more mobile (or has a higher migration rate) more of the element accompanies the acid rocks than is the case for gold. The result is a low Au/Ag ratio in the deposits in near-surface acidic rocks and higher ratios in the deeper rocks of more basic composition. It will be recalled from the discussion above that Bruce (1943) and Badalov and Badalova (1967) noted a wall-rock effect on the Au/Ag ratio; others including Fitzgerald *et al.* (1967 *a,b*) have, however, noted no wall-rock effects on the ratio.

In some Canadian gold deposits the writer has noted a wall-rock effect on the Au/Ag ratio of the ores similar to that described by Ol'shevskiy (1975). A few examples will serve to illustrate this statement. Many gold deposits in (basic) greenstone rocks have relatively high ratios compared with similar deposits in (acidic) quartz-feldspar porphyries, granites and syenites regardless of age. Some basic examples are: Yellowknife, Northwest Territories (Archean greenstones – 5); Bralorne, British Columbia (Mesozoic greenstones and diorites – 5.5); Pickle Crow, Ontario (Archean greenstones and iron-formation – 11.5); Delnite Mine, Timmins, Ontario (Archean greenstones – 11); and Chesterville Mine, Larder Lake, Ontario (Archean greenstone – 18). Some acidic examples are: Box Mine, Lake Athabasca (Archean granite – 3); Howey Mine, Red Lake, Ontario (Archean quartz porphyry – 3); Young Davidson Mine, Matchewan, Ontario (Archean syenite – 4.3); and Kirkland Lake, Ontario (Archean syenite – 5.8). The effect is also notable in the many mines of the Timmins (Porcupine) area of Ontario. Mines such as the Moneta, Delnite, Aunor and Buffalo Ankerite, mainly in Archean greenstones, have high Au/Ag ratios for their ores (7–11.6), whereas those such as the Hollinger, McIntyre and Paymaster, which are partly in or near masses of quartz-feldspar porphyry, have lower ratios (3–5.2). An extreme example of this effect can be seen by comparing the general Au/Ag ratios in the various ores in the McIntyre Mine. The gold-quartz ores mainly in greenstones have a Au/Ag ratio equal to 5, whereas the cupriferous ores in altered porphyry have a ratio of 0.14 (Boyle, 1976*a*).

It should be remarked, that there are numerous exceptions to the basic and acidic wall-rock effect on the Au/Ag ratio in some gold belts, but statistically speaking it appears that there is some validity in the phenomenon. The reasons for the effect are, however, obscure. Ol'shevskiy (1975) attributes the effect to volcanic agencies, but this cannot be the case where granites are concerned. It seems more probable that the effect is due to differential reactions between the gold-bearing solutions or diffusion currents and the two kinds of wall rocks – basic and acidic. Basic rocks are marked by a much higher degree of carbonatization, sericitization and sulphidization than are acidic rocks in most gold deposits (*see* the next section on wall-rock alteration processes). This has involved a greater removal of CO_2, K and S from the solutions or diffusion currents, a feature that has probably markedly affected the stability of the various gold and silver complexes. Gold complexes, such as those with S, As, Sb and Te, were probably rendered more unstable than similar silver complexes, thus leading to the precipitation of a greater proportion of gold in basic rocks than in those of acidic composition. This explanation is only a suggestion and seems to follow from our experiments (Boyle *et al.*, 1975) mentioned in Chapter II in the section on natural waters – actually, the whole problem of the wall-rock effect on the Au/Ag ratio requires much more detailed and sustained investigations. Finally, there may be some confirmatory evidence with respect to the acidity of the environment and the precipitation of gold from the recent research by Diman (1976). He observed that the purity (fineness) of gold in association with pyrite depends essentially on the sulphur regime and the acidity of solutions rather than on the temperature of deposition.

Konstantinov (1977) has characterized volcanogenic gold deposits on the basis of their Au/Ag ratios, which he notes range from 10:1 to 1:1000. Within this range he characterizes three types falling within the following ratios: 10:1 to 1:1, 1:1 to 1:5 and less than 1:20.

Those deposits with high Au/Ag ratios (10:1 to 1:1), including Cripple Creek in Colorado, Vatukoula in Fiji and certain deposits in the Soviet Union, comprise a gold-tellurium type. All have high tellurium contents, 5 to 20 times that of gold, the tellurium being combined mainly with Au, Ag, Bi and Hg and also in the native state. Most of these goldfields are rich but small in area (5–15 km^2). The native gold usually has a high fineness; in some deposits much or nearly all of the gold is present as telluride minerals. The productive gold-telluride shoots are usually shallow, localized within 1000 m from the surface and pass into gold-polymetallic shoots at greater depths. The deposits are mostly concentrated in local faults and fractures mainly in subvolcanic formations constituting necks, dikes and bodies of eruptive breccia that form part of the volcanic belts of island arcs (on an oceanic or transitional type of crust) or ophiolite zones. The host volcanic rocks are generally alkaline basalts and andesite-basalts of the calc-alkaline series with roughly equal proportions of sodium and potassium. Prior to the mineralization events an increase in alkalinity in the late volcanic phases is notable and is manifest by minor extrusions of dacite and rhyolite.

Volcanogenic deposits with ratios 1:1 to 1:5 such as those in Romania (Transylvania), Japan and eastern U.S.S.R. are marked by a strong development of adularia and relatively small amounts of sulphides compared to the previous type. The gold occurs in small nuggety masses and has a low fineness. Such deposits are commonly localized in volcano-tectonic depressions, calderas and grabens, frequently in radiating faults and fissures or in similar structures related to block faulting. Most of these deposits constitute large goldfields (30–50 km^2) and are confined to volcanic belts of continental interior type and less frequently to fragments of island arcs developed on a continental crust. The host volcanics are andesites, andesite-basalts and andesite-dacites. The subvolcanic facies are commonly more acidic in composition than the overlying rocks and are characterized by higher alkalinity with an increase in the relative role of potassium.

The third type, characterized by ratios of less than 1:20, includes the silver-rich Comstock Lode, various other argentiferous-auriferous deposits with ratios as low as 1:1000 in western United States, Mexico and the eastern regions of U.S.S.R. All are characterized by high amounts of argentite (acanthite), with native silver and/or electrum in some deposits. Base metals and occasionally tin occur in higher amounts in the associated sulphide ores. The deposits constitute goldfields covering considerable areas (70–100 km^2). Many of the deposits are localized in extensive tension faults and fissures related to tectonic uplifts and block faulting. The host volcanic rocks exhibit an increasing alkalinity with time resulting in preore acidic rocks of trachy-liparitic composition followed by deposition of potassium-rich gangue minerals such as adularia and hydromicas.

An attempt can now be made to systematize the above data together with that recorded in the numerous papers mentioned in the Selected bibliography. It should, however, be noted that when one attempts to compile the Au/Ag ratios of deposits on a worldwide basis one is beset with many inconsistencies and difficulties, too numerous to mention here. Some of these are related to the inadequacy or lack of suitable assays, others derive from the process of compiling from production data where the grade and percentage of recovery of the two precious metals are unknown. Despite these problems Table 43 has been compiled from the worldwide literature according to the type of deposit in which gold and silver occur. The following features are apparent:

1. Only three types of hypogene deposits have Au/Ag ratios consistently greater than 1. These are the auriferous quartz-pebble conglomerate deposits, certain skarn-type deposits and most, but not all, gold-quartz veins in Precambrian, Paleozoic and Mesozoic rocks. Tertiary deposits in certain belts also have ratios greater than 1, but they are relatively uncommon. All the other hypogene deposits generally have Au/Ag ratios less than 1. Gold placers always have Au/Ag ratios greater than 1.

2. The Au/Ag ratios in disseminated deposits in shales and sandstones (Kupferschiefer and 'red bed' types) are generally low, indicating a relatively high degree of mobility and concentration of silver during the formation of these particular deposits. Since these deposits probably are the result of low temperature aqueous processes, the ratios are what one would expect because silver is much more soluble and hence more mobile and more easily concentrated under such conditions.

3. In the auriferous quartz-pebble conglomerate deposits the range of the Au/Ag ratios is generally narrow, but there are some significant differences in some deposits such as the Witwatersrand, which have been intensively studied by Hargraves (1963), Von Rahden (1965), Saager (1969) and Viljoen (1971).

Hargraves (1963) found that low grade samples have high silver contents and vice versa, and that the silver content of bullion from individual reefs varies as a funciton of the relative elevation of the reef, i.e., the bullion of the shallow reefs has a higher silver content than deeper reefs of comparable grade. Hargraves (1963) interpreted these compositional gradients as the result of chemical rather than physical (detrital) processes and stated that in terms of the modified placer hypothesis for the origin of the gold, the gradients imply considerable redistribution of silver relative to gold during the 'solution' stage. This is, therefore, again a case of the greater mobility of silver compared to gold during relatively low temperature processes.

Table 43. Au/Ag ratios of a variety of mineral deposits

Type of deposit	Au/Ag ratio (range)	Remarks
Shale deposits (Kupferschiefer type)	0.006–0.025	
Disseminations, veins, etc, in sandstones (red-bed type)	0.003–0.01	Variable
Quartz-pebble conglomerates (Rand type)	5–20	Witwatersrand bullion ranges between (5.8–15.6) (Hargraves, 1963). On channel samples of the Ventersdorp Contact Reef and Main Reef the Au/Ag ratios range from 0.6–13.7 (Von Rahden, 1965)
Disseminated lead-zinc deposits in carbonate rocks (Mississippi Valley–Pine Point type)	0.001–0.1	Few data
Skarn-type deposits	0.005–10	Variable
Massive sulphides (Ni-Cu Sudbury type)	0.03–0.07	Shcherbina (1956*a*) gives 0.07 for Norilsk, and Hawley (1962) gives 0.03 for Sudbury ores
Porphyry copper type	0.001–0.1	Few data
Polymetallic massive sulphides (Flin Flon–Noranda–Bathurst type)	0.006–1	Average about 0.025
Polymetallic massive sulphides (Kurokô type)	0.005–0.05	Average about 0.02
Polymetallic veins, mantos, etc. (Keno Hill–Sullivan–Cœur d'Alene type)	<0.0001–0.02	
Gold-quartz veins, lodes, etc. (Precambrian, Paleozoic and Mesozoic age)	1.37–12.5	Average about 4.2
Gold-quartz veins, lodes, etc. (Tertiary age)	0.005–0.33	Average about 0.05
Native silver-Co-Ni-As-Bi-U veins (Cobalt-Jáchymov type)	<0.0001–0.01	
Hot spring siliceous sinters	<1	
Gold placers (all types and ages)	>1	

Van Rahden (1965) thought that his data, which show wide variations in the apparent fineness (and hence in the Au/Ag ratios) of channel samples from the same elevations and stopes in the Ventersdorp Contact Reef and Main Reef, could be ascribed to the presence of silver minerals (mainly native silver) in the ore. The silver minerals, he felt, were due to the redistribution of silver relative to gold during the solution stage of the modified placer theory suggested to explain the Rand deposits. Van Rahden further concluded that his results did not tend to confirm Hargraves' (1963) hypothesis that the silver content of the reefs varied with elevation. He recommended electron microprobe studies of the ore to resolve the problem.

Addie (1964), commenting on Hargraves' paper, considered that the increase in the Au/Ag ratio in the Witwatersrand deposits with depth is due to exsolution of a silver-gold solid solution as the temperature changes. By this he apparently meant that since the silver is more mobile it migrates out of the system. He thought that the increasing Au/Ag ratio signalled an approach to a thermal centre and postulated a thermal source for the mineralization.

Saager (1969) investigated the Au/Ag ratios of individual gold particles and of ore samples from the Basal Reef conglomerate horizon of the Upper Witwatersrand System in the Orange Free State Goldfield (South Africa). The values for individual gold grains were found to be exceptionally constant at about 12.3, whereas the Au/Ag ratios of the ore samples have markedly lower values and show a large variation. Saager concluded that these values indicate that the detrital gold has been homogenized during transportation and sedimentation and that part of the original silver content has been redistributed. He thought it probable that the first refining of detrital gold particles occurred in streams that eventually drained into the Witwatersrand basin. Further redistribution of the silver relative to the gold took place in the littoral zone of the basin, where the conglomerates were reworked by wave action and erosion. He further contended that supergene enrichment of gold might also have taken place close to the original shoreline. These processes, he believed, accounted for a decrease in the Au/Ag values of ore samples towards the northwest in the area investigated. Furthermore, Saager hypothesized that gold has probably been homogenized during the metamorphic period of the Witwatersrand System, when pseudohydrothermal transport and redeposition of certain constituents took place. Finally, he suggested that the main portion of the silver content of the original alloy that was redistributed during the various processes outlined above is now present as finely dispersed silver minerals. The hypothesis of an elevation control of the Au/Ag values, as postulated by Hargraves, was found to be improbable.

Viljoen (1971) carried out an electron microprobe analysis of gold grains in situ in samples from a variety of reefs from the Rand. The silver content of individual gold grains varied from 0.3 to 32.1 per cent. Variations were noted in one and the same sample, and some gold grains that were analyzed showed that they were considerably enriched in silver along the periphery. Contrary to the findings of other investigators no discrete silver-bearing minerals were encountered, but the silver content of galena in the Dominion Reef was up to 3 per cent and in the Vaal Reef up to 2 per cent. The data presented indicate an overall average of 10 per cent for the silver content of the gold particles.

4. There are few data on the gold content of the 'Mississippi Valley type' lead-zinc deposits, and hence a precise knowledge of the Au/Ag ratios is not obtainable. Our limited data on these deposits show that silver is generally greatly enriched compared to gold, and the ratios are, therefore, always low. This indicates a higher mobility for silver compared to gold, a feature that one would anticipate since these deposits are probably concentrated by low temperature connate or circulating groundwater.

5. The Au/Ag ratios in skarn deposits are exceedingly variable and apparently related to the mineralogy and hence

the chemistry of formation of these deposits. Taking some Canadian deposits as examples one notes that a deposit such as the Nickel Plate at Hedley, B.C., where arsenic is abundant, is characterized by a high Au/Ag ratio (5–10), and in this respect is similar to certain gold-quartz veins enriched in arsenic. Probably the mode of transport of the two noble metals during the formation of these two types of deposits has been the same, although the geological setting differs. It would seem that the migration of gold was greatly enhanced by the presence of arsenic in the diffusion or solution system. On the other hand the New Calumet and Tetreault lead-zinc deposits in the Grenville Province both have low Au/Ag ratios (<0.1) and simulate the normal type of silver-rich Pb-Zn deposits. These deposits are not particularly enriched in arsenic, but contain significant amounts of antimony present in tetrahedrite, polybasite, stibnite, etc. Hence, it seems probable that antimony has had a marked influence on the mobility of silver.

6. Massive nickel-copper sulphides of the Sudbury type, generally associated with basic igneous rocks, seem to have a narrow range of Au/Ag ratios from about 0.03 to 0.07, indicating a considerable enrichment of silver over gold at the relatively high temperatures at which these ores are supposed to have formed. Both the silver and gold appear to follow copper, although it would be interesting to know the precise relationships with arsenic and antimony. According to Hawley (1962) chalcopyrite is the principal argentiferous mineral at Sudbury.

7. The porphyry copper deposits tend to have a relatively low Au/Ag ratio judging from the few good data available. Certainly many of the high-grade copper and lead-zinc skarn and vein deposits associated with the porphyry copper bodies are greatly enriched in silver compared to gold. The situation in the Timmins area with respect to a porphyry copper deposit and the gold-quartz veins is of interest. There, silver is much more abundant in the McIntyre Cu-Mo orebody than in the gold-quartz veins that occur in the same environment. In the copper orebody the Au/Ag ratio is about 0.14, whereas in the gold-quartz deposits the ratio is about 5, in agreement with the general overall ratio (7) in the Porcupine (Timmins) gold belt.

In British Columbia the Au/Ag ratio of the various porphyry copper deposits shows a wide variation. The Island Copper orebodies on Vancouver Island have a ratio approaching 0.2 calculated from production records. Other deposits such as the Granisle, Bethlehem, Brenda and Lornex orebodies have low ratios, ranging from 0.002 to 0.095. The investigations of the Island Copper metallurgical staff and our work on the ores indicates that most of the gold in the Island Copper orebodies is present in the native state. The silver is largely in, or associated with, chalcopyrite.

Kesler (1973) investigated the gold abundance in porphyry copper deposits with respect to copper and molybdenum. He suggested that porphyry copper deposits are divisible into geologically real copper-molybdenum and copper-gold classes. The compositional variation, he observed, was thought to have been caused by primary compositional differences between mineralizing systems (that is, the genetically associated intrusive rock and its juvenile hydrothermal phase), or by differing chemical responses of similar systems to distinctive tectonic features (such as level of emplacement or permeability of wall rock) or wall-rock chemistry. Kesler concluded that the obvious important factor for such consideration is the possibility that copper-molybdenum and copper-gold porphyry copper deposits could represent mineralizing systems of fundamentally different compositions and, as such, could be analogous to petrologic variations among areas of different tectonic setting.

8. The massive polymetallic sulphide deposits (Flin Flon–Noranda–Bathurst type) nearly all have relatively low Au/Ag ratios, which average about 0.025. Hutchinson (1973) found the ratios in these types of deposits, mostly in volcanic terranes, to range from 0.0002 to 0.60. In some of these deposits silver follows lead and in others an association with copper is evident. Gold seems to follow arsenic and is concentrated in pyrite and arsenopyrite in some deposits; in others, gold appears to be associated mainly with chalcopyrite, galena and sphalerite. The occurrence of gold and silver in most deposits of this type is not well defined, and more research on this feature of the geochemistry of the deposits is desirable.

A number of deposits contain argentiferous tetrahedrite, and other silver-bearing sulphosalts, and hence there may be a relationship between silver and antimony. Other silver and gold minerals such as argentiferous tennantite, argentite, native silver, electrum, gold and sylvanite have been recorded from a number of deposits, and these may be responsible for part of the gold and silver content of the ore.

In the 'kurokô type' of polymetallic sulphide deposit silver is also greatly enriched with respect to gold, the ratio Au/Ag usually falling in the range 0.005 to 0.05. Much of the gold in these ores occurs as electrum, which is commonly about 770 fine. The electrum is most commonly associated with galena, sphalerite and tetrahedrite-tennantite in the ores. The silver in addition to being present in electrum is contained in tetrahedrite-tennantite, acanthite, stromeyerite, pearceite, polybasite and a number of other silver sulphosalts.

9. The polymetallic veins and the native silver – cobalt–nickel arsenide veins have the lowest ratios of all the various types of auriferous hypogene deposits, indicating an extreme mobility for silver and practically no mobility for gold during their formation. The reasons for the great enrichment of silver in these deposits are indeed obscure but must be related either to the source of the mineralizing media or to particularly good agents of transport for silver. In many of the polymetallic veins and mantos silver follows lead closely, and there appears to be a close association with antimony and sometimes with arsenic. In other deposits of this type silver and copper exhibit a close affinity. High contents of manganese in siderite are characteristic of a number of silver-rich polymetallic veins. In the Ni-Co arsenide type there is often an association of silver with antimony, as witnessed by the presence of antimonian silver, allargentum and dyscrasite in these deposits. The association of the native silver with the arsenides is, however, often so close as to suggest that the silver migrated as some highly mobile Ag-As complex. Why gold in quantity did not go along with the silver is an enigma since the element tends to follow arsenic in other types of deposits. An answer may lie in the complex composition of the solutions or diffusion currents that precipitated the silver and arsenides. These

solutions were evidently greatly enriched in carbonate as witnessed by the general abundance of calcite, dolomite and other carbonates in the veins. Silver carbonate is relatively soluble, especially where CO_2 is in excess, and this feature could account for the relatively great mobility of silver during the formation of the Ag-Ni-Co-As veins. On the other hand gold does not seem to be capable of forming a carbonate, and in fact there are indications from some of the natural associations of the element that solutions or diffusion currents highly enriched in CO_2 actually depress the solubility and mobility of gold.

10. Gold-quartz veins in Precambrian, Paleozoic and Mesozoic rocks generally have Au/Ag ratios greater than 2, and these average about 4.2. There are, however, some local exceptions to this generalization that seem to correlate with the mineralogy and hence chemistry of formation of the deposits. At Yellowknife, Northwest Territories, veins with arsenopyrite and pyrite tend to have normal ratios for this class whereas others with a high stibnite and sulphosalt (antimony) content tend to have ratios equal to or less than 1. This suggests that the mobility of silver was considerably increased when antimony was present in quantity in the chemical system. Another example in the Canadian Shield is the Ross Mine, near Ramore, Ontario. Some of the orebodies in this mine have an Au/Ag ratio of about 0.7, much lower than those in the nearby Porcupine and Kirkland Lake camps (~7). Two periods of mineralization are evident in the Ross Mine; the first consists of blue quartz veins with pyrite, chalcopyrite, sphalerite, galena and gold, and the second is marked by the development of quartz-dolomite veins containing pyrite, sphalerite, galena, tennantite, chalcopyrite, gold and native silver (Jones, 1944). In the first period of mineralization gold predominated over silver, and in the second, the reverse is true. Here again we note a preponderance of silver where carbonate was present in some abundance in the chemical system. Other gold mines in the Canadian Shield where unusual Au/Ag ratios prevail in the ores include the Ronda in the Matachewan area of Ontario where the ratio approximates 0.58, the Ardeen (Moss) in the Thunder Bay district of Ontario with a ratio of approximately 0.17 and the Berens River deposit where the ratio is highly anomalous being as low as 0.023. These deposits have an unusual mineralogy, most containing abundant argentiferous galena or other silver minerals especially sulphosalts and tellurides. The mineralogy of the Berens River deposit in northwestern Ontario is unusual for Archean greenstone belts. Its ores consisted of abundant sphalerite and galena, with pyrite, pyrrhotite, chalcopyrite, tetrahedrite, dyscrasite, native silver and ruby silvers in a gangue of quartz, carbonates and actinolite (Oliver, 1949). No native gold was observed despite the fact that the ores averaged 0.25 oz Au/ton. The Ardeen (Moss) Mine was characterized by abundant silver tellurides.

11. Gold-quartz veins, lodes and stockworks in Tertiary andesite, dacite, rhyolite and other associated volcanic rocks generally have ratios less than 1 in contrast to their counterparts in older rocks. Many of the young (Tertiary) deposits are, however, mineralogically different from the older deposits in that a number of them contain much larger amounts of galena, chalcopyrite, sphalerite, tetrahedrite-tennantite, argentite and silver sulphosalts. In this respect they are analogous to many of the polymetallic veins and have similar ratios. By contrast, veins with a simple mineralogy, containing essentially native gold, gold tellurides, pyrite and minor amounts of the base metal minerals, such as those at Cripple Creek, Colorado, have Au/Ag ratios greater than 1.

12. Siliceous sinters precipitated from present-day hot springs generally have Au/Ag ratios less than 1 (Table 22). In this respect they are similar to many of the Tertiary deposits.

13. Gold placers always have Au/Ag ratios greater than 1 regardless of the age of the source deposits. This is due to the natural refining action that takes place during weathering processes. It seems highly probable that at one time or another much of the gold in secondary zones and in placers was in solution, and that during this process most of the accompanying silver was removed. This seems to follow naturally from the chemistry of the two elements. Silver is much more soluble than gold in ground and surface waters and is not as readily reduced to the metal. A natural separation is, therefore, inevitable.

Some investigators would perhaps disagree with this interpretation. For instance, Mertie (1940) is of the opinion that the differences in the fineness between lode and placer gold are related to depth of erosion of the mother lodes. Thus, the placer gold, which is usually of great fineness, probably comes from the apical near-surface zones of lodes whose hypogene gold was of greater fineness than the deep-seated parts of the lodes that are now exposed to view. This opinion is certainly contrary to that held by MacKay (1944), who showed almost conclusively that the gold in the oxidized zones of a number of mines in Tanzania and Nigeria has been greatly increased in fineness as the result of oxidation and secondary enrichment processes.

14. Deposits in older geological formations are frequently richer in gold than those in younger formations. There are, however, numerous exceptions to this generalization in a number of mineral belts, Cripple Creek (Tertiary) being a good example.

15. The evidence that the Au/Ag ratio is an index of temperature of formation or recrystallation of deposits is conflicting. In some deposits the ratio increases with depth, in other deposits a decrease or erratic behaviour is evident. However, few precise studies of the variation of the Au/Ag ratios of single ore shoots or veins with increasing depth have been made, and judgment on the effectiveness of the ratio as a temperature index should be reserved. Furthermore, the assumption that the deep parts of the deposits were formed at temperatures higher than the near-surface parts may be in error. On a statistical basis, however, there is some evidence to support the contention that deep-seated (high temperature?) deposits have a higher Au/Ag ratio than those formed at intermediate depths or near the surface, presumably under conditions of lower temperatures.

16. There is considerable evidence to show that the Au/Ag ratio increases in primary halos with proximity to ore shoots in most types of epigenetic gold deposits. This increase is also manifest in a vertical sense in the vein mineralization, increasing downward toward ore shoots in some cases and upward toward the shoots in others. Both upward and downward increases in the Au/Ag ratio have been recorded from some deposits.

17. Shcherbina's (1956*a*) view that gold is predominant in telluride ores whereas silver is dominant in selenide ores appears to be true. The analogous situation that gold tends to follow arsenic, and that silver is associated with antimony, is likewise marked on a statistical basis. There are, however, some striking examples where gold is enriched in antimony-bearing ores and silver in arsenical ores.

18. Gold and silica (quartz) show a marked association whereas silver tends to be concentrated in an environment where carbonates are abundant. The association of silver with manganiferous siderite, manganiferous calcite or dolomite and rhodochrosite is striking in some districts. In Tertiary deposits gold shows a similar relationship to the manganiferous carbonates and silicates. (*See* the section on mineral associates.)

19. Evidence from many auriferous belts throughout the world indicates that there is a wall-rock effect on the Au/Ag ratio, the ratio being higher where the wall rocks are basic than where acidic rocks are the hosts. There are a number of exceptions to this generalization, but statistically the phenomenon seems to hold in a number of gold belts. The reasons for the effect are obscure but probably involve the stability of the complexes of gold and silver in the transporting solutions or diffusion currents. Basic rocks appear to have the greatest effect in rendering gold complexes unstable, thus permitting proportionally higher amounts of gold to be precipitated than is the case with acidic rocks. The wall-rock effect on the Au/Ag ratio merits further detailed investigation.

20. The Au/Ag ratio in deposits seems to depend on regional metallogenic peculiarities in a crude way, if only certain types of deposits are considered. When all deposits are brought into the picture only diffuse relationships emerge. There are perhaps as many gold-quartz deposits with ratios greater than 1 in the Circum-Pacific belt of America as there are other deposits with ratios less than 1. The same is true for the Appalachian belt and in some greenstone belts of the Canadian Shield. The ratios seem to depend more on the type of deposit (i.e., its mineral constitution and hence chemical history) than on its position in the earth's crust.

The purity or fineness of native gold in deposits is a complicated problem that has not received the attention it merits. With the development of the electron probe this problem is more amenable to a detailed attack, and it is to be hoped that we shall soon see some detailed research work on gold from all types of deposits, and also from single deposits with respect to the degree of fineness with increasing depth and other parameters.

The purity of native gold is considered in a general way in Chapter II. There, it was stated that a large number of metals may substitute in trace, minor or major amounts in gold. Of these Ag is frequently a minor or major constituent; Cu is commonly also present, and elements like Fe, Hg, Bi and Pt may be a minor or trace constituent of native gold.

The literature invariably emphasizes the fact that the fineness of gold in placers is higher than that in the deposits from which it came. This circumstance is discussed as some length in this chapter in the section on placers. Here, it is sufficient to state that this is due to a natural refining action predicated on the greater mobility (solubility) of silver compared with gold in the supergene environment. The silver is leached out in the general placer environment leaving the residual gold depleted in silver. Another feature repeatedly referred to in the literature is the commonly observed fact that young (Tertiary) deposits (some call these near-surface or epithermal deposits) have high contents of silver in their native gold. These deposits are the home of electrum. No hypothesis to explain this phenomenon seems to have been put forward. Perhaps it is metallogenetic in nature and cryptic from the present plane of observation. On the other hand the phenomenon may have something to do with the recycling of gold and silver in the crust with time. It is common to find late secretion veins in gold deposits greatly enriched in silver. Veins formed by what the writer has called a late extraction process from pre-existing sulphides in rocks and deposits are invariably rich in silver. The rich silver deposits at Cobalt may be an extreme example of this phenomenon (Boyle and Dass, 1971*b*). As mentioned later, the Tertiary deposits may have originated by this process of extraction of Au and Ag from underlying rocks – hence their native gold tends to be greatly enriched in silver.

Fisher (1945, 1950) has examined the fineness of gold with respect to the types of deposits. His general observations and conclusions, only slightly paraphrased are as follows.

Lodes formed under epithermal conditions at shallow depths typically contain gold from about 500 to 700 fine. In this zone the correspondence between gold fineness and temperature of formation appears to be close, and the gold fineness furnishes a sensitive measure of the conditions of deposition. Deposits formed in Late Tertiary times under shallow cover carry gold about 500 fine as a rule, while those formed near the bottom of the zone or in what Graton has called the leptothermal zone – transitional from the epithermal to the mesothermal – contain gold about 700 fine, possibly ranging up to as much as 800. Studies made by R. V. Gaines consequent upon the publication of Fisher's original paper (Fisher, 1945) furnish an illustration of this type of variation. Samples were collected at various horizons in the Timmins Ochali-Berlin Mine near Yaramul in the Antioquia region of Colombia, South America. This lode is considered to have been formed near the top of the mesothermal zone. Gold fineness in the primary ore was found to increase downwards from 680 to 760 over a vertical distance of 1300 ft. These figures provide a satisfactory confirmation of the deductions as to the probable variation in gold fineness with depth that were drawn from a general study of the subject, namely that the fineness of gold shows a general increase with depth of deposition, which implies high temperature and pressure, and appears to be correlated more closely with temperature.

Exceptions to the rule that epithermal deposits carry comparatively low grade gold occur only in deposits in which silver is conspicuously absent and insufficient silver was present in the ore-bearing solutions to form an alloy appropriate to the environment. As long as sufficient silver is present, even though it is only just sufficient, low-grade gold will be found in epithermal deposits.

If tellurium is present, it will combine with the gold and silver in proportions appropriate to the relative concentrations, so that the gold telluride, calaverite, will be formed in regions like Cripple Creek, where little silver is present in the ore, and silver-gold tellurides where silver is abundant. Gold appears to have a greater affinity for tellurium than for silver, and will combine with it in preference to silver. If excess gold and silver are present after all the tellurium has been taken into combination as tellurides, they will be deposited as an alloy of fineness typical of the environment, e.g., in epithermal deposits such as those of Karacs-Czebe, Transylvania, where low fineness gold is formed.

Deposits in the mesothermal zone normally carry gold from 750 to 900 fine, but the fineness may be higher in areas poor in silver. A very common fineness in lodes of the mesothermal zone is 850 to 870.

It is not impossible that under certain special chemical conditions, or in the presence of certain minerals, gold of lower than the typical fineness may be deposited in mesothermal deposits, but such cases, if they exist at all, are rare exceptions.

Deposits of the hypothermal zone always contain gold in excess of 800 fine, no matter how much silver may be present in the ore.

Gold of very high fineness, 990 or more, is generally the result of oxidation under conditions favourable for the complete removal of silver. Mount Morgan, Queensland and Kalgoorlie, Western Australia are excellent examples. High fineness is also often associated with the oxidation of telluride ores, e.g., Fiji and Cripple Creek, Colorado.

Alluvial gold, being derived from the oxidized ore, is of higher fineness than the average of the vein gold and shows an increase in value downstream due to surface refining action, as the size of the grains decreases.

Eales (1961, 1968) examined the fineness of gold in a number of Rhodesian mines (Olympus, Lonely, Horn and Turk). These deposits occur in Precambrian greenstone belts, some in iron-formations and sheared greenstones and others in granite gneiss, the principal mineralization consisting of quartz, pyrite, pyrrhotite, chalcopyrite, sphalerite, sulphosalts, gold tellurides and native gold. In the gold recovered from the four deposits he noted that high-grade ore generally contained silver-poor gold whereas silver-rich gold was more typical of low-grade ore. Mineragraphic studies indicated that gold of early crystallization, which occurs enclosed by sulphides such as chalcopyrite or sphalerite, contains more silver than that which crystallized late. Eales concluded that variations in fineness from place to place in a given deposit depend on the stage of the paragenesis during which the bulk of the gold was precipitated, and that the relationship between fineness and tenor arises out of the protracted crystallization of the gold in the richer sections. Accordingly, he reasoned that ore shoots are characterized by the association of late-stage minerals with a high proportion of late gold, which is poor in silver.

Sakharova (1969*b*) and Sakharova and Demidov (1972) examined the composition of native gold by X-ray spectral (electron probe) methods in the Darasun quartz sulphide deposit, Transbaikal, U.S.S.R. The elements investigated in the gold were Ag, Cu, Fe, Bi, Pb, Te, Sb, As and S. Their data indicated that gold of the same generation varied in composition both within the deposit and, in places, within the same polished section. For most grains the content of gold and silver was constant in the central part, but the concentration of gold decreased and that of silver generally increased in the marginal zone. The concentration of gold at the centre of grains ranged from 93 to 76.5 per cent, but it diminished at the edge to values ranging from 10.5 to as low as 2 per cent. The increase in silver content of the same interval equaled 2 to 10 per cent. The zones ranged in width from 3 to 15μ. The decrease in gold concentration in the marginal zones is clearest for grains in sulphides. For disseminations in quartz the gold content does not vary. For granules at the boundary between ore minerals and quartz the gold content does not vary on the side of quartz, but it diminishes by 2 to 2.5 per cent on the side of ore minerals (sulphides, tellurides).

Sakharova (1969*b*) concluded from the data that an exchange of atoms by diffusion is possible in natural mineral aggregates. She further postulated that there is interdiffusion between gold and the metals in its host sulphides. The metals that can diffuse into gold are iron and copper, i.e., elements that have small ionic radii and resemble gold in atomic structure in the metallic state. Elements of the anionic type, such as sulphur and tellurium, however, cannot diffuse into native gold, nor can high-valent cations like antimony and arsenic.

Finally, Sakharova and Demidov (1972) showed that the Au/Ag ratio in the ores of the Darasun deposit is 5 to 20 times higher than the average for the earth's crust. The Au/Ag ratio is lower in beresitized rocks than in the ore-bearing veins.

Yugai (1971) found that the purity (fineness) of gold increased with depth from 606 to 771 over a vertical range of 288 m in gold-quartz deposits in sheared sediments and Hercynian granites. He attributed this to the effects of supergene alteration processes.

An extensive investigation of the fineness and other characteristics of native gold in 15 gold deposits formed at shallow depth (mostly epithermal deposits of Cretaceous-Tertiary age, e.g., Belaya Gora, Agatovskoye) in the eastern U.S.S.R. by Berman *et al.* (1973) shows that the situation is extremely complex. They noted wide fluctuations in the fineness of the gold within single deposits but relatively uniform values in single ore shoots. In some cases the maximum difference was 600 units between different ore shoots. In some cases different parts of single gold particles showed a maximum difference of 120 units in fineness. Nevertheless average values generally indicated that the early generation of gold in most deposits was higher in fineness than later generations. The fineness of the native gold is also influenced by its host mineral. In some deposits the gold in the sulphides has a much higher fineness than that in the quartz and other gangue. Berman *et al.* (1973) think this may be typical only of gold-silver deposits with an excess of silver in the depositing solutions (shallow depth deposits), and mention investigations by N. L. Nikolayeva that indicate the native gold in sulphides in deeper mesothermal deposits has a lower fineness than that in the quartz and other gangue.

A number of recent data on the fineness of gold in deposits in U.S.S.R. is contained in the two volumes edited by Petrovskaya (1974). In one of the northern Kazakhstan deposits of Silurian age mineralized with quartz, arsenopyrite and sulphosalts, Sher found the average fineness to be 870±70. The main part of the gold with a fineness of 870 was deposited in the quartz gangue. In the eastern Yakutian gold-quartz-sulphide-sulphosalt deposits, Gamyanin and Leskova found a complex situation with respect to the composition (fineness) of the native gold. In many deposits the composition of the gold was erratic and changed with respect to the geological and physico-chemical conditions of its formation. In some oreshoots formed over a short dip or strike interval the composition of the gold was relatively constant. At the Karal'veemskoe deposit in western Chukotka the mineralization is essentially gold-quartz veins and irregular bodies with pyrite and arsenopyrite in Late Mesozoic diorite dykes and in greenstone diabase sills in Triassic phyllites, quartzites and schists. In the deposit Ol'shevskii and Kisterov found by histogram that the fineness of the gold is bimodal indicating two generations, one with an average fineness of 890 and the other 910. And finally, in the Muruntau deposit in Uzbek S.S.R. (For description *see* the section on deposits in this chapter.) Voronich *et al.* noticed that the gold and silver content of the deposit depends on the composition of the host rocks and is independent of depth. The deposit also lacks vertical zoning.

To summarize the data available on the variations in the fineness of gold in deposits one can say that the situation is generally complex, and in some cases each gold belt and commonly each deposit seems to have its own characteristics. In some auriferous deposits there is an indication that the early deposited gold is more silver-rich (lower in fineness) than that deposited later in the paragenetic sequence. At Kirkland Lake for instance the gold in early pyrite tends to be silver-rich (low in fineness) whereas the later generations of free gold are silver-poor (high fineness) (Blomfield *et al.,* 1936). Eales (1961, 1968), as noted above, also found a similar relationship in some of the gold mines in the Precambrian terrane of Rhodesia. Many of these investigations were carried out be reflectometry measurements about which there is some controversy as to their accuracy (Stumpfl, 1969). The author's investigations in this matter are equivocal, but on a statistical basis there is an indication that the early gold in sulphides is lower in fineness than the later generations of free gold. This probably only applies, to old (Precambrian and Paleozoic) deposits, since there is undoubted evidence that the late generations of gold in certain Mesozoic-Cenozoic deposits are exceptionally rich in silver compared with early generations.

There appears to be considerable variation of fineness with depth from deposit to deposit. In some cases there is an increase in the fineness of native gold with depth, a feature explained by some as due to an approach to a hot centre; silver being more mobile migrates farther from the hot centre than gold. In other deposits there is an indication that the fineness decreases with depth, and in still others there is no particular relationship, the fineness remaining relatively constant.

The data are equivocal concerning lateral zonations of the fineness of native gold in deposits with respect to thermal centres of intrusion or granitization. There are indications that the fineness of native gold in deposits near these centres is higher than in more remote deposits. Numerous aberrations seem, however, to complicate this picture and more data are required before definite statements can be made.

Within individual deposits there are often major differences in the fineness of native gold from oreshoot to oreshoot. Most individual oreshoots, however, generally record a relatively uniform fineness when their dip and strike dimensions are short.

In some deposits as revealed by microprobe studies the gold grains have a relatively uniform silver composition; in others they are markedly heterogeneous being zoned or having silver-rich or silver-poor sectors. Numerous deposits also seem to have marked intragrain compositional differences with respect to silver and other lattice constituents. These inhomogeneities obviously have a marked effect on systematic variations within deposits, features that must always be considered by those doing work on the fineness of gold in deposits.

There is obviously a wall-rock effect on the fineness of native gold, but the details are obscure and the whole problem requires detailed investigation.

The effect of temperature on the fineness of native gold in deposits should be carefully investigated, especially where deposits have a great vertical range and pass from low grade metamorphic facies into intrusives. Some of the data at hand suggest that there is a temperature effect, native gold near hot centres or fronts being finer than that in remote sites. This is most noticeable where intrusives such as dykes cut preexisting auriferous oreshoots. Adjacent to the dykes the native gold is often much finer than that at a distance from the dyke.

All of this discussion has centred essentially on the fineness (i.e., the silver content) of native gold. It seems probable that the contents of Cu, Te, Hg and the various other elements in lattice sites in native gold would also vary in certain systematic ways with depth, wall rock and other geological and geochemical features of the deposits. This problem has not been investigated in any detail within gold belts or deposits, although some preliminary work has been done as noted in the section on native gold in Chapter II. Particularly pertinent in these matters are the papers by Desborough *et al.* (1970, 1971) and Berman *et al.* (1973).

Oxidation processes have a marked effect on the fineness of gold in deposits. In many deposits the free gold in the oxidized zones is considerably finer than that in the hypogene zones. The range in fineness of hypogene gold is usually 700 to 925; that for native gold in oxidized zones is commonly 900 to 999. In placers the gold is normally finer than the hypogene gold in the original deposits, although there are situations where there is an equivalence in the fineness of the two types of gold.

> A study of the changes in rocks contiguous to orebearing fissures is essential to a thorough understanding of the genesis of such deposits.
> —W. Lindgren, 1901

Hypogene wall-rock alteration processes associated with epigenetic gold deposits

The term "wall-rock alteration" is difficult to define precisely since the phenomena accompanying it are extremely diverse, and the patterns developed vary with numerous geological and chemical parameters. In a general way wall-rock alteration can be defined as the mineralogical and chemical changes manifest in the host rocks of epigenetic deposits by the mineralizing media that may have been aqueous solutions, gases, melts or diffusion currents. Two general types can be differentiated –

hypogene wall-rock alteration developed contemporaneously or nearly so with the precipitation of the hypogene ore and gangue minerals and supergene wall-rock alteration produced as a result of supergene processes of oxidation and reduction. Here, only hypogene wall-rock alteration will be discussed in any detail. The supergene alteration processes in gold-bearing deposits are described in Chapter IV.

The type, degree and the lateral and vertical extent of wall-rock alteration attending epigenetic gold deposits depends on numerous interacting factors both geological and chemical. Briefly these are:

1. The nature of the host rock, specifically its mineralogical and chemical constitution, grain size, porosity and permeability, and the degree of shearing and fracturing adjacent to the sites of precipitation of the ore and gangue minerals.
2. The nature of the ore and gangue forming medium, specifically its state (liquid, gas or diffusion current), its chemical composition and its temperature and pressure.

Studies of wall-rock alteration associated with gold deposits are valuable in two respects. Firstly, they provide, together with chemical data on the ore and gangue elements and liquid inclusions in these minerals, an idea of the chemical constitution of the ore forming medium, and secondly they are useful in prospecting for ore. A few brief comments on the first of these features will be made in this section. The second aspect is dealt with in Chapter V.

The data used in the preparation of this section have come from many sources, principally published descriptions in the world literature together with data obtained by the writer during his long study of gold deposits.

The common mineral alterations in epigenetic mineral deposits are so well known that they hardly need mentioning. However, to avoid repetition, some of the common mineral alterations in all types of rocks are listed below.

Mineral	*Alteration products*
Quartz	Generally resists alteration. Quartz may be replaced by sericite, feldspar, carbonates and other minerals in some alteration zones.
Potash feldspar	Frequently resistant in alteration zones. In intense phases of alteration it yields sericite, hydromuscovite, clay minerals, alunite, epidote, zoisite, quartz and albite.
Plagioclase	Sericite, hydromuscovite, clay minerals, alunite, epidote, zoisite and quartz. Calcium component may yield calcite; aluminum component may give rise to chlorite or biotite. Frequently replaced by various sulphides. Calcic varieties of plagioclase often lose calcium and yield albite.
Muscovite	Hydromuscovite, clay minerals and quartz.
Biotite	Hydrobiotite, chlorite, sericite, hydromuscovite, clay minerals, epidote and quartz. Iron and magnesium components may yield carbonates (ankerite); iron and titanium components give rise to magnetite, rutile and leucoxene. Frequently replaced by various sulphides.
Hornblende	Biotite, hydrobiotite, chlorite, sericite, clay minerals, epidote and quartz. Calcium, iron and manganese components may yield carbonates, pyrite and/or magnetite. Titanium component gives rise to rutile and leucoxene. Frequently replaced by various sulphides. May yield serpentine minerals and talc under certain conditions.
Augite	Hornblende (uralite), biotite, chlorite, quartz and other products mentioned under biotite and hornblende. May yield serpentine minerals and talc under certain conditions.
Olivine	Serpentine minerals, talc, magnetite or hematite. Frequently carbonatized with development of ankerite. More rarely altered to chlorite, pyroxenes and amphiboles.
Magnetite	Frequently replaced by pyrite. Titanium component may yield leucoxene or rutile.
Ilmenite	Iron component may yield pyrite. Titanium component yields leucoxene or rutile.
Sphene	Leucoxene or rutile, calcite and quartz.
Zircon	Generally unaltered.
Apatite	Frequently unaltered. May be destroyed in intensely altered zones.
Carbonates	Various calcium-magnesium-manganese silicates, talc and serpentine minerals. Frequently entirely replaced by quartz.

Summary accounts of many of the features of wall-rock alteration, some pertaining to auriferous deposits can be found in the various papers and monographs by Lindgren (1901), Morey and Ingerson (1937), Schwartz (1947, 1950, 1955, 1959), Sales and Meyer (1948, 1950), Lovering *et al.* (1949), Lovering (1950), Stringham (1952), Khitarov (1957), Burnham (1962), Hawkins and Roy (1963), Korzhinskii (1965), Meyer and Hemley (1967) and Boyle (1970).

Roslyakova and Roslyakov (1975) give an extensive summary of the types of alteration associated with the various types of gold deposits in U.S.S.R. In addition they discuss the habit of gold and numerous other trace elements in the primary (endogenic) halos of these deposits (*see also* Chapter V).

Types of wall-rock alteration associated with epigenetic gold deposits

A number of types of hypogene wall-rock alteration are associated with epigenetic gold deposits. The most important of these, together with some brief general notes on their mineralogy and chemistry, are as follows. Details are discussed in subsequent sections.

Skarnification consists generally of the development of calcium-magnesium-manganese-iron silicate minerals, quartz, magnetite and a host of other minerals in limestones, dolomites or calcareous shales and schists. Gold deposition may or may not be associated with the process. The calcium-magnesium-manganese–iron silicates formed include olivine, wollastonite, garnet, pyroxenes, amphiboles, uralite and scapolite. Quartz, plagioclase and carbonates are generally present, and there may be a development of many minerals containing the mineralizers, S, H_2O, F, Cl and B, such as pyrite, pyrrhotite, serpentine, tourmaline, axinite, scapolite, vesuvianite, topaz, micas and fluorite. The process of skarnification may be essentially isochemical with removal of CO_2; more generally, however, it involves the introduction of SiO_2, Mg, Fe and the volatiles S, As, B, F, Cl and H_2O. Under these conditions removal of CO_2 is usually extensive.

In some skarn deposits the introduction of gold, economic sulphides, scheelite and various oxides appears to have taken place simultaneously with the formation of the principal skarn minerals. In other skarn deposits the introduction of the economic minerals appears to be later than the formation of the skarn. In this case the skarn is altered, the main effects being replacement of pyroxene by tremolite and actinolite and the development of quartz, epidote, calcite, sericite and chlorite or serpentine.

Amphibolitization and *pyroxenitization* involve the development of amphiboles and pyroxenes respectively in the wall rocks of auriferous deposits. Minerals accompanying these types of alteration include feldspar (commonly albite), epidote, tourmaline, biotite, magnetite, pyrite, pyrrhotite, garnet, biotite and occasionally andalusite and cordierite. Both amphibolitization and pyroxenitization are characteristic of certain deep-seated (high temperature?) gold-quartz veins and impregnation deposits mainly in igneous rocks of intermediate and basic composition but also in certain gneissic sedimentary terranes. Some of these deposits seem to be transitional to skarn bodies.

Feldspathization consists of the development of secondary feldspars in the host rocks of epigenetic gold deposits. Albitization is perhaps the most common, but the development of potassium feldspar (microcline, orthoclase or adularia) is common in certain types of deposits. Chemically the process may involve the introduction of K, Na and Al, although in some deposits these elements are simply rearranged, and the system is essentially isochemical. The genesis of hydrothermal K-feldspar (adularia), by replacement of andesine phenocrysts and by precipitation processes, in an active geothermal environment at Wairakei, New Zealand is discussed by Steiner (1970). In the Finish gold occurrence in the Okhotsk-Chukotka volcanic belt, U.S.S.R., Eremin (1970) noted that the near vein adularization of the liparite ignimbrites was superimposed on a preore propylitization stage. He also noted that the amount of adularization increased with depth.

Tourmalinization consists of the development of tourmaline in the wall rocks of certain types of epigenetic gold deposits. Chemically it involves the introduction of boron and in some cases Mg, Fe, Na, Ca, Al and Li. In zones of intense tourmalinization in shales and schists there is frequently a decrease in the SiO_2 and CO_2 content of the altered rock.

Fluoritization involves the introduction of fluorine into wall rocks with the development of fluorite. *Topazization* implies the development of topaz and an introduction of fluorine. *Greisenization* is an all-inclusive term involving the processes of fluoritization, topazization, sericitization and tourmalinization. These combined processes entail the conversion of feldspar, and other constituents of granitic and pelitic rocks in places, to aggregates of quartz, topaz, tourmaline, fluorite and commonly lepidolite or lithium-bearing muscovite. Judging from the available analyses there is a general introduction of fluorine, boron, lithium, tin and iron, and small abstractions of silica, calcium, sodium and potassium; alumina and magnesium generally remain relatively constant. All of these various fluoriferous alterations are generally associated with tin, tungsten and beryllium mineralizations. They are relatively rare in auriferous deposits. Fluoritization is, however, common in some Tertiary gold deposits, e.g., Cripple Creek, Colorado; topazization is notable at the Brewer Gold Mine, Chesterfield County, South Carolina; and greisenization is marked in some auriferous deposits bearing tin and tungsten minerals in the Mesozoic-Cenozoic tin-tungsten-gold belts of the far eastern U.S.S.R.

Silicification consists of the development of secondary quartz, jasper, chalcedony, chert, opal or other varieties of silica in the wall rocks of epigenetic gold deposits. By another terminology it also includes the development of various silicates in the host rocks, particularly in carbonate rocks or calcareous shales and schists. As noted above the latter process is called skarnification.

The chemistry of silicification is varied and depends essentially on the type of host rock, which is affected by the process. In carbonate rocks there is generally a major introduction of SiO_2 and a wholesale removal of Ca, Mg, Fe, CO_2 and other constituents. In silicate rocks SiO_2 may be redistributed within the host rocks, that is, leached in one place and added in another.

Biotitization is an uncommon type of alteration in gold deposits but occurs in certain places. It usually involves the development of biotite or hydrobiotite from various cafemic silicates. During the process H_2O and K are introduced, and some SiO_2 may be extracted. Less commonly the constituents of biotite, including K, Mg, Fe, Al and SiO_2, are all introduced into the rock.

Chloritization is one of the most common types of alteration in gold deposits. In many cases it develops directly by the hydrous alteration of cafemic silicates. During this process H_2O is introduced and some SiO_2 may be removed. In other cases constituents of chlorite, including Mg, Fe, Al and SiO_2, are introduced into the rock.

Sericitization is perhaps the most common of all of the types of wall-rock alteration in gold deposits developed in acidic, intermediate and basic igneous and metamorphic rocks. It consists of the development of potash mica, generally sericite or hydromuscovite, as a result of the hydration of feldspars or from the rearrangement of K, Al and SiO_2 within intensely altered wall rocks. Chemically, sericitization generally involves the introduction of K and H_2O into the rocks affected, and there is usually a removal of some SiO_2, Fe and Ca. The development of fuchsite and mariposite, the chromium-bearing micas, in basic and ultrabasic rocks adjacent to gold-quartz veins usually does not imply an introduction of chromium. Rather this element appears to be redistributed during the chemical breakdown of magnetite, pyroxenes and amphiboles, the principal chromium-bearing minerals in the rocks. The development of the mica, roscoelite, probably has a similar origin deriving its vanadium from magnetite, etc.

Granitic rocks, granite gneisses, quartz porphyries and certain types of schists heavily sericitized, albitized in places and impregnated with pyrite are called 'beresites' by the U.S.S.R. geologists. The term *beresitization* is commonly used in the Ural goldfields and in other gold-bearing districts of U.S.S.R. Numerous studies of the process have been carried out. According to Glukhov (1974) the wall rocks are generally enriched in K, CO_2 and Ca and exhibit depletions in Fe^{3+}, Al and SiO_2. Sericite and Ca-Mg carbonates are the principal resultant minerals. According to the same investigator the deposition of gold occurs during the late beresitization – early silicification (quartzitization) stages. Grabezhev (1973, 1974) states that beresites and greisens are formed within a similar temperature interval of 270 to 400°C. According to the same author fluorite is generally absent in beresites because the F concentration in the solutions from which gold was precipitated was lower than in those which gave rise to rare metal deposits (Be, Mo, W, Sn, Rb, Li). In the latter the F content often ranges from 937 to 8510 ppm, whereas in beresites the range is much smaller, 550–740 ppm. Most of the fluorine in beresites is in the micas (sericite).

Beresitization is particularly complex in certain deposits and may be zoned. Gavrikova *et al.* (1973) observed such a situation in the Itakinsk gold-sulphide deposits of eastern Transbaikal. There, they noted by analyses complex patterns with respect to Na and K as the veins were approached, although in a general way the K_2O/Na_2O ratio showed an increase towards the auriferous deposits. In addition they noted a vertical zonation over 1 km, the most outstanding feature being the development of seybertite (a high temperature brittle mica) at deep horizons and lower temperature chlorite in the upper horizons. They attributed this phenomenon partly to a temperature gradient along the direction of flow of solutions. Abdukhayumov (1973) and Babaev and Abdukhayumov (1974) also noted marked lateral zonations in beresitized rocks in the gold-sulphide deposits of Terekkan, U.S.S.R. The zoning comprised an external chlorite-albite-sericite-carbonate zone, an intermediate quartz-carbonate-sericite-pyrite zone and inner quartz-sericite-pyrite and quartz zones adjacent to the orebodies. During the beresitization process the content of Na, Mg and other bases decreased and S and CO_2 were introduced. The Si and K contents increased in the inner zone. In some deposits Al displayed an inert behaviour.

The development of the sodium mica, paragonite, is not common but occurs in some alteration zones where soda metasomatism is a marked feature of gold deposition. The process can be called *paragonitization;* it usually involves introduction or rearrangement of considerable amounts of Na and H_2O.

Carbonatization consists of the formation of secondary carbonates in the host rocks of epigenetic gold deposits. The phenomenon is particularly common in intermediate to basic rocks. *Dolomitization* consists of the formation of dolomite in the wall rocks of deposits usually at the expense of calcium carbonates, but also in places at the expense of magnesium silicates and other minerals. The process is relatively uncommon in gold deposits, but an analogous process *ankeritization,* which consists of the formation of ankerite, $Ca(Fe,Mg,Mn)(CO_3)_2$, is especially common.

The chemical processes involved in carbonatization are complex and depend essentially on the type of host rock affected. The ankeritization of basic and intermediate intrusive rocks and volcanics, such as frequently occurs in gold-quartz deposits, appears to require only the introduction of CO_2, the other constituents of ankerite such as Ca, Fe, Mg and Mn coming from the chemical breakdown of amphiboles, pyroxenes and feldspar. During this process much SiO_2 is removed and probably transferred to the veins where it crystallizes as quartz.

Sideritization and other types of carbonatization of sedimentary rocks, especially quartzites and sandstones, generally requires the introduction of nearly all of the components of the carbonates formed in the rocks.

Basic and ultrabasic rocks, heavily carbonated, sericitized and pyritized are called 'listwänites' by the Soviet geologists. The term *listwänitization* is commonly used in the Ural goldfields and in other auriferous districts of the U.S.S.R. Kashkai (1964) and Goncharenko (1970) have discussed the zoning and chemistry of listwänites in some detail. Briefly the metasomatic development of listwänitized rocks follows the sequence: (1) initial formation of serpentine-actinolite-chlorite rocks (with few carbonates) grading to serpentine-chlorite-carbonate rock; (2) intermediate stage of formation of serpentine-brucite-carbonate rocks containing hematite and quartz and grading to talc-chlorite-carbonate and talc-carbonate rocks; (3) listwänite stage of the mariposite listwänites and the quartz-carbonate listwänites and their varieties; (4) final stage of veinlet formation of quartz, carbonates and other components of listwänites and (5) a postlistwänite stage during which sulphides and other components, genetically related to younger hydrothermal activity, were precipitated in the listwänites.

The main characteristic of listwänitization is the conversion of serpentine into talc and/or carbonates. The chemical composition of listwänite is variable and is controlled by zonal factors and the composition of the host rocks. In general there is an introduction of K, Ca, Al, CO_2 and H_2O and an abstraction of SiO_2.

Pyritization and *arsenopyritization* are two of the most common types of alteration in gold deposits. They consist of the development of disseminated pyrite and arsenopyrite in the host rocks of epigenetic deposits. In many types of deposits only sulphur and arsenic are introduced, the iron coming from the breakdown of iron silicates and oxides as McKinstry (1957) has suggested. In other types of deposits all of the components of pyrite and arsenopyrite are introduced.

Propylitization is a paricularly common type of alteration associated with gold-quartz and polymetallic deposits in basic and intermediate intrusive rocks and volcanics. The principal secondary minerals developed are chlorite, epidote, zoisite, leucoxene, carbonates, sericite, feldspar, clay minerals, pyrite and arsenopyrite. Propylites commonly form the fringe zone of highly altered rocks where sericitization, carbonitization and pyritization are intense.

Chemically, much water is introduced during propylitization, and there may also be additions of CO_2, S and As. Some SiO_2 is generally extracted during the process, and there may be losses of Na, K and the alkaline earths in some districts; in others K and Na may be enriched.

Propylitization tends to pervade large volumes of rock in many districts and may, therefore, not be directly connected with epigenetic gold deposits. In places it appears to grade imperceptibly into the greenschist facies of regional metamorphism.

Rocks that are heavily propylitized exhibit several types of alteration including chloritization, carbonatization, pyritization and sericitization. The term propylitization is, therefore, a broad inclusive one.

Much has been written on the processes of propylitization in the past, especially with reference to the Mesozoic-Cenozoic gold deposits of Europe and the United States (Lindgren, 1933; Emmons, 1937), and numerous papers have appeared in recent years on the subject, most dealing with Tertiary rocks and deposits in which propylitization is especially marked (Szeky-Fux, 1964; Rusinov, 1968; Kazarinov *et al.,* 1970; Vasilevskii, 1972). There are many questions about the causes of propylitization, the source of the volatiles, such as CO_2 and H_2O, that take part in the regional phenomena, and the relationship of propylitization to mineral (gold) deposition. These problems lie more in the field of petrology and cannot be discussed here. About all that can be said with assurance respecting gold deposits is that many, especially those in Tertiary andesitic terranes, appear to be closely associated with extensive propylitization linked in some manner or other with a high mobility of potassium resulting in potash metasomatism of the propylitized rocks and the wall-rock alteration zones of the gold-quartz veins.

Argillic alteration consists of the development of clay minerals in the wall rocks of epigenetic gold deposits. The common clay minerals found include kaolinite, montmorillonite, dickite, illite and halloysite. The principal chemical effect appears to be the introduction of water, and there may be a removal of some SiO_2, Fe, K, Na, Ca and Mg, depending on the type of rock affected.

Alunitization is common in some low temperature (epithermal) gold deposits principally in acid and intermediate volcanic rocks. It generally consists of the development of alunite, $(K,Na)Al_3(SO_4)_2(OH)_6$, and quartz in feldspathic rocks, the alunite being largely the result of alteration of the feldspars. Chemically, the alteration generally involves an introduction of S and H_2O and removal of some SiO_2, Na, Ca, Mg and Fe.

Certain stability parameters for alunite were determined by Hemley *et al.* (1969). According to them a fairly high H_2SO_4 concentration is required in solutions before alunite can be produced in equilibrium with muscovite, kaolinite or K-feldspar. They also found that consistent with geologic observation alunite-kaolinite (including dickite or pyrophyllite) are the most likely products of strong hydrolytic (advanced argillic) types of alteration in either hot spring or higher temperature environments, whereas muscovite-alunite is favoured by higher temperature as well as higher potassium concentrations.

Some of the more recent studies of alunitization association with auriferous deposits are those by Harvey and Vitaliano (1964) for the Goldfield district, Nevada; Lodder (1966) for the gold-alunite deposits of Rodalquilar, southeast Spain; Takeuchi and Abe (1967) for a number of deposits in Japan; and Wang (1973*a*,*b*) for auriferous deposits in Taiwan.

In general, alunitization signifies acid attack by H_2SO_4 on the alkaline silicates of the wall rocks, particularly on the feldspars. In some deposits, however, the components of alunite, including K, Na, Al and SO_4 seem to have been introduced, at least locally, possibly as soluble sulphates.

Alunitization may be hypogene and/or supergene in origin in some gold deposits.

Hematitization is a type of alteration that frequently accompanies gold deposits, particularly those containing uranium. It is also found in a variety of other deposits often in syenitic rocks as at Kirkland Lake, Ontario. The presence of hematite generally indicates a low partial pressure of sulphur in the mineralizing solutions or diffusion currents.

The iron producing the hematitization may or may not be introduced. In some cases there is abundant chemical evidence that the element has been introduced as ferric iron into the wall rocks; in other cases where pervasive hematitization is present the iron is probably only redistributed while undergoing oxidation from the ferrous to ferric state. In the latter case some iron may actually be leached.

Serpentinization and the closely allied development of talc *(talcification)* generally consists of the formation of serpentine and talc in ultrabasic rocks such as dunite, peridotite and pyroxenite. Serpentinization and the development of talc may also occur in crystalline limestones and dolomites. The effect is marked in some gold-quartz and other types of deposits in ultrabasic rocks.

Serpentinization and the development of talc in ultrabasic rocks generally only involves the introduction of H_2O and the redistribution of the other constituents of the rocks. Where serpentine and talc are developed in limestones and dolomites there is generally an introduction of SiO_2 and H_2O and frequently some Mg.

Hydration is nearly universal in all types of wall-rock alteration in gold deposits. It indicates an introduction of water that is fixed either as hydroxyl or as water of hydration in the various alteration minerals. *Dehydration* involves the removal of water, such as takes place in the formation of certain types of wall-rock alteration zones.

Phosphatization is common in the alteration zones of some gold deposits. It involves the introduction or rearrangement of phosphate resulting mainly in the development of apatite. Some gold deposits exhibit this feature to a moderate degree.

Pyrophyllitization consists of the development of the hydrous aluminum silicate, pyrophyllite. In most types of epigenetic gold deposits this type of alteration is apparently rare. Pyrophyllite is, however, a very common mineral in the matrix of the auriferous quartz-pebble conglomerates of the Witwatersrand.

Zeolitization consists of the development of zeolites such as stilbite, natrolite, heulandite, chabazite, etc. The widespread process is frequently not associated with mineral deposition. The process, however, frequently accompanies native copper deposits in amygdaloidal basalts and is also associated with certain types of gold and silver veins. In all occurrences the zeolites are often accompanied by calcite, prehnite, pectolite, apophyllite and datolite.

Regularities of wall-rock alteration associated with gold deposits with respect to types of host rocks

A survey of the world literature of gold deposits, combined with studies at the Geological Survey indicates that wall-rock alteration, exhibits a certain regularity with respect to the types of host rocks. This regularity is discussed below, but it should be clearly understood that there are numerous exceptions to the generalizations given here.

For purposes of discussion the various types of host rocks are divided into the following categories:

1. Acidic rocks – include granites, rhyolites, quartz-feldspar porphyries and the acidic metamorphic equivalents of these rocks such as granite gneisses, mica schists, etc.

2. Intermediate and basic rocks – include granodiorite, syenite, nepheline syenite, monzonite, dacite, diorite, andesite, phonolite, gabbro, diabase, basalt and their metamorphic equivalents such as amphibolites, pyroxenites, etc.

3. Ultrabasic rocks – include dunite, peridotites, pyroxenites and their metamorphic equivalents.
4. Normal shales, slates, phyllites and derived schists.
5. Sandstone, conglomerate, quartzite, greywacke, arkose and their metamorphic equivalents.
6. Carbonate rocks.

Acidic rocks

In gold deposits the most prevalent types of wall-rock alteration in acid rocks are sericitization, argillization and the development of quartz and pyrite. The principal chemical features are the introduction of water and usually small amounts of CO_2 and the redistribution and loss of a number of constituents. Silica is generally liberated and may crystallize as quartz in the alteration zones or be transferred to the veins or other dilatant zones. Sodium and occasionally potassium are leached, and sulphur is generally introduced together with some iron. This type of wall-rock alteration is typical of many gold and base metal districts and of the copper-molybdenum porphyry deposits.

Feldspathization combined with the development of tourmaline and mica is common in the wall rocks of certain slightly auriferous pegmatites in granites, granite gneisses and schists. The phenomenon generally involves the introduction of some Na and K and variable amounts of B and H_2O. Feldspathization is only moderately common in the wall-rock alteration zones of gold-quartz and base metal deposits in acidic rocks. In some goldfields, however, there is often a marked development of albite or adularia.

Alunitization occurs in certain near-surface (epithermal Tertiary) gold deposits in granites, rhyolites and quartz-feldspar porphyries. It is, however, not as common as in intermediate rocks such as dacite, latite, etc. (*see* below).

Tourmalinization is marked in certain gold-quartz deposits in acidic rocks, especially in granodiorite. Biotitization, chloritization, carbonatization, zoisitization and epidotization are rather uncommon types of wall-rock alteration in acidic rocks, although there are many notable examples of these particular types in a few gold deposits.

Beresitization is a common alteration process in many parts of the world where gold deposits are localized in granite dykes, quartz-feldspar porphyry dykes and irregular bodies and other types of granitic rocks.

Intermediate and basic rocks

In gold deposits the most common types of wall-rock alteration in intermediate and basic rocks are chloritization, carbonatization, sericitization, pyritization, arsenopyritization, alunitization and propylitization. There is frequently a lateral zonation of these types of alteration with respect to the veins, lenses and lodes. Adjacent to the deposits the wall rocks exhibit an intense phase of sericitization, carbonatization and pyritization (also arsenopyritization) that grades imperceptibly into a phase characterized by chloritization, weak carbonatization and pyritization. In some types of deposits the latter phase grades into rocks that are areally propylitized and contain much chlorite, epidote, carbonate, etc.

Carbonatization, sericitization, pyritization and chloritization of intermediate and basic rocks generally involves an introduction of CO_2, H_2O, S and frequently As. There is usually a major extraction of SiO_2 that is probably transferred to the vein sites in most cases. Constituents like Fe, Ca, Mg and Mn remain more or less constant. Na and K exhibit a variable habit. In some cases there is a local redistribution of alkalis, especially K; some Na is leached from the more intensely altered zones in places.

Argillic alteration is comparatively rare in intermediate and basic rocks older than the Tertiary. In Tertiary and Quaternary volcanic zones, however, this type of alteration is common in gold deposits, particularly in those in andesites and their corresponding pyroclastics.

Alunitization is a frequent type of alteration in certain near-surface (epithermal Tertiary) deposits of gold, silver and base metals in dacites, latites and monzonites (e.g., Goldfield, Nevada). Alunite is generally developed together with much quartz at the expense of the feldspars. Chemically much S and H_2O are introduced, and there is a removal of some SiO_2, Na, Ca, Mg and Fe in intensely alunitized rocks. Carbonates are rare in alunitized rocks.

Zeolitization is common in certain vesicular basalts and other basic rocks containing native copper, gold and silver deposits. Minerals, such as orthoclase, chlorite, epidote, pumpellyite, prehnite, datolite, quartz and calcite, frequently accompany the zeolites. Analyses of altered zeolitized basalts appear to be lacking in the literature, and it is difficult to determine what changes take place during this particular type of alteration. Presumably H_2O, CO_2, B, Na, Ca and SiO_2 are introduced in most cases. Zeolitization is relatively rare in gold deposits older than those of Tertiary age. In the latter and in some Quaternary deposits this type of alteration may occur, but it is not common.

Feldspathization occurs in some intermediate host rocks but is relatively rare in basic rocks, although developments of albite are common in the alteration zones of certain gold-quartz and gold-bearing polymetallic deposits in some districts.

Tourmalinization is moderately abundant in some gold-quartz and other types of deposits developed in intermediate and basic rocks. Biotitization may also occur in places.

Ultrabasic rocks

The predominant type of alteration in ultrabasic rocks is serpentinization and the development of talc. In some gold districts serpentinites and other types of ultrabasic rocks show a marked carbonatization (ankeritization) and a development of magnesite and chromium-bearing fuchsite or mariposite. In such situations there is generally a marked loss of silica that is probably transferred to the veins where it crystallized as quartz. Listwänitization is common in some auriferous deposits in basic and ultrabasic rocks in U.S.S.R.

Normal shales, slates, phyllites and schists

Shales, slates and schists adjacent to gold deposits generally exhibit less tendency to alter compared with acidic, basic and ultrabasic igneous rocks. There are, however, certain well marked types of alteration in shales, slates and schists and these usually show some regularity.

In high grade metamorphic terranes and in the contact aureoles of granitic intrusions, calcareous shales may exhibit skarnification in the vicinity of gold, copper and other types of high temperature deposits.

Tourmalinization is particularly common where shales, slates and schists are the host rocks for gold-quartz veins. Commonly a band of tourmaline borders both contacts of the quartz veins.

Feldspathization is generally not extensive in the wall rocks of most types of gold-quartz veins, although in some districts albitization is characteristic.

In many metalliferous districts normal shales, slates and schists tend not to exhibit extensive alteration zones in the vicinity of gold-quartz and other varieties of epigenetic gold and polymetallic deposits. In such districts the quartz veins are more or less frozen against the wall rocks. In other districts, however, such deposits may be marked by one or more of the following types of alteration: silicification, tourmalinization, biotitization, chloritization, sericitization, carbonatization, pyritization, arsenopyritization and argillic alteration. Of these tourmalinization, sercitization, chloritization, carbonatization and pyritization appear to be the most common.

Sandstone, conglomerate, quartzite, greywacke, arkose and their metamorphic equivalents

The so-called 'red bed' uranium, vanadium, copper, lead and silver deposits, usually devoid of gold, are generally, but not always, in bleached beds of sandstone, sandy limestone, sandy shale, conglomerate or arkose. The bleaching in most cases is said to be due to the reduction of ferric iron to the ferrous state. There is also generally a development of kaolinite and frequently some chlorite both within the deposits and in the enclosing rocks. The chemistry of the bleaching has not been investigated in sufficient detail in any of the deposits to draw adequate conclusions. Some analyses done for the writer on the rocks from Nova Scotia deposits suggest that the principal chemical changes in the bleached rocks, compared to the normal red sandstones and shales, are reduction of ferric iron and the introduction of some K, Al and H_2O.

Gold deposits in quartz-pebble conglomerates are excluded here because of their controversial origin. Most geologists consider these deposits to be modified placers. The various alterations that these deposits have undergone are considered in detail in the next section of this chapter.

Veins and other types of epigenetic gold deposits in sandstone, quartzite, greywacke and arkose are not generally marked by extensive alteration zones. Where alteration is present, as in some gold districts, the predominant types are tourmalinization, feldspathization, carbonatization, pyritization, arsenopyritization and choritization.

Carbonate rocks

The principal types of high temperature alteration in carbonate rocks are skarnification and silicification. These usually go hand in hand. In some gold deposits in skarns there may also be a weak to moderate development of tourmalinization, chloritization, serpentinization or the formation of talc. In the Muruntau deposits in Uzbekistan, U.S.S.R. the calcareous siltstones, shales and phyllites associated with the gold-bearing stockwork deposits are extensively altered in many stages during which formation of actinolite, pyroxene, feldspars, chlorite, biotite, tourmaline, sericite, quartz, pyrite, pyrrhotite, arsenopyrite and gold took place.

Skarnification is an extremely variable type of alteration that appears to depend on the initial composition of the carbonate rocks. Generally there is a major development of calcium-iron-magnesium-manganese silicates, quartz and magnetite. The chemical changes in the altered rock vary from district to district. A generalized compilation of the chemical data available in the literature indicates that the additions are mainly SiO_2, Fe, Mg, Ti, K, Al, S, B, F, Cl, P and H_2O, plus a number of metals of which the most significant are Cu, Mo, W, Sn, Pb, Zn, As, Au, Ag, Bi, Pt and Be. Not all of these additions occur in any one place. The principal subtraction is CO_2.

The alterations found in medium- to low-temperature deposits in carbonate rocks are dolomitization and silicification. The first is relatively rare in gold deposits. The chemical changes in dolomitization generally involve an increase in Mg and frequently some Mn and a little Fe. There may or may not be a loss of calcium. Silicification involves the introduction of SiO_2 and a general elimination of Ca, Mg, Mn, Fe and CO_2.

Timing of wall-rock alteration, open and closed systems and the nature of ore-forming solutions giving rise to auriferous deposits

The timing of the introduction and abstraction of the various constituents that participate in wall-rock alteration is a most complex problem – one that has not yet been satisfactorily solved. According to one school the various exchanges are an integral part of one surge of mineralization, the various reactions and exchanges taking place in a complex diffusion system within a relatively short geological interval. The other school advocates a number of successive but discontinuous surges or pulses, each producing characteristic effects that depend on the nature of the mineralizing medium, the nature of the wall rocks, the sequence of fracturing and other factors. One stage of wall-rock alteration may be superimposed on another, and the chemical and mineralogical relationships may be very complex indeed. The whole problem of the timing of wall-rock alteration is intimately associated with mineral paragenesis and zoning, two subjects that are too extensive and complex to be discussed at this point; they are, however, dealt with later in this chapter. The student of ore genesis and wall-rock alteration should always be aware of the two possibilities and should strive to obtain unequivocal criteria for the solution of the chemical and mineralogical relationships.

The problem of open and closed chemical systems in wall-rock alteration processes associated with epigenetic gold deposits remains essentially unsolved and will remain so until detailed material balance calculations are carried out throughout all parts of the various types of auriferous deposits, including the ores and the lateral, sub and supra alteration haloes. Similarly the problem of equilibrium in the various chemical reactions in wall-rock alteration is unanswered. Probably most reactions are not equilibrium reactions in the commonly accepted chemical sense. It is more fruitful to approach wall-rock alteration from a dynamic (kinetic) viewpoint, since diffusion seems to play such a large part in all of the processes.

One final aspect of the chemical and mineralogical regularity in wall-rock alteration in gold deposits that needs mentioning is the tendency of dissimilar rocks to converge to a uniform type of alteration. This feature has been noted by numerous investigators and is evidently due to prolonged attack by the mineralizing medium. There are for instance numerous references in the literature of interbedded slates, greywackes, amphibolites and other quite dissimilar rocks being all converted to carbonate-sericite rocks and of quartz porphyries, tuffs and shales intensely altered to an aggregate composed of quartz, sericite and clay minerals. Silicification of carbonate rocks, shales and sandstones, likewise yields a convergent type of alteration in some deposits that is indistinguishable with respect to the host rock except by very detailed studies.

It has long been recognized that the ore-forming medium may be either gaseous, an aqueous solution, meltlike or in the nature of a diffusion current of mobile ions or complexes. The features of wall-rock alteration in auriferous deposits do not seem to give unequivocal criteria for any of these mechanisms of transport, although there are certain trends that may be indicative.

The features of auriferous skarn zones suggest extensive diffusion of SiO_2 and other constituents into the carbonate rocks and CO_2 out of them. It also seems probable that diffusion of mineralizers, such as H_2O, S, As, F, Cl and B, played a large part in the formation of auriferous skarns.

The formation of the various types of auriferous veins and lodes probably took place mainly by diffusion in the deep zones of the earth and by precipitation from aqueous solutions under near-surface conditions. In certain cases, such as in the slightly auriferous massive nickel-copper ores, the sulphides may have crystallized from melts, since many have little or no associated wall-rock alteration. It seems impossible from studies of wall-rock alteration to decide which process – diffusion or precipitation from aqueous solutions – was the important agent in the formation of auriferous veins and lodes. Other criteria (Boyle, 1963) must be brought to bear on this problem. Whatever the agent or mechanism, it is certain that water played a large part in the formation of auriferous veins. Other volatiles, such as CO_2, S, As, Se, Te, Sb, B and F, have played a leading role in the formation of certain types of gold deposits. Wall-rock alteration zones associated with auriferous deposits rarely show the effects of chlorine metasomatism, a feature that might lead one to suspect that chlorides are not as important in the transport of gold and other metals as some investigators would have us believe. On the other hand sodium chloride is particularly abundant in some hot springs and thermal waters and is found in liquid inclusions. The reason for the low abundance of chlorides in wall-rock alteration zones and in auriferous veins may be the great solubility of most of these compounds. In other words, they are largely removed from the deposits at a late stage by the mineralizing solutions or diffusion currents.

Judging from the chemistry of wall-rock alteration, the constituents of most auriferous veins and lodes were deposited from an aqueous medium that was highly fluxed with CO_2 and S in most cases and with As, Sb, Se, Te, Bi, B, F and Cl in some cases. The gold was probably transported mainly as sulphide, arsenide, antimonide or telluride complexes, and most of the accompanying metals were carried as complex bicarbonates, sulphides, arsenides, antimonides, selenides, tellurides, bismuthides, fluorides or chlorides. Quartz and many of the constituents of the other gangue minerals, such as Fe, Ca, Mg and Mn, may have been largely derived from the adjacent wall rocks.

The pH of the ore forming medium is difficult to assess from wall-rock alteration studies of auriferous deposits. In some cases there is evidence that the solutions or diffusion currents were acid and that they gradually became alkaline by reaction with the wall rocks. In other cases they evidently were neutral or slightly alkaline. In most cases where direct measurement of or calculation from hot spring data have been done the solutions are at or near the neutral point.

Further discussion of the origin of epigenetic gold deposits is reserved for the last section of this chapter. Some typical examples of wall-rock alteration in various types of gold deposits are now discussed.

Examples of wall-rock alteration associated with gold deposits

The examples to be described follow the general scheme of types of deposits mentioned at the beginning of this chapter. Some of the data are taken from the published literature; the remainder were obtained during the study of gold deposits by the writer in Canada and other countries.

Auriferous porphyry dykes, sills and stocks; auriferous coarse-grained granitic bodies, aplites and pegmatites

Deposits in granitic rocks containing indigenous gold are few and most are not of economic importance. Some pegmatites carry small amounts of gold that may have crystallized with the pegmatitic minerals. The common types of wall-rock alteration associated with the formation of these pegmatites are feldspathization, tourmalinization, silicification and development of mica (frequently Li-bearing); development of beryl, apatite and garnet; and biotitization of amphibolites in places, indicating an introduction of K. These processes are described in some detail by Cameron *et al.* (1949) and Jahns (1955).

Where gold occurs in porphyry dykes and other granitic rocks as a late mineralizing phase, the granitoids are commonly fissured and silicified. There is often an introduction of tourmaline, and the feldspars are sericitized and frequently carbonated. Pyrite, arsenopyrite and other sulphides fill the fissures in part and invade the granitoid walls up to distances of 1 ft or more. These manifestations of the mineralization are similar to those described subsequently under granitic rocks and need not be further dealt with here.

Auriferous skarn-type deposits

These deposits are characterized by the development of various silicates of calcium, magnesium, manganese, iron and aluminum, especially garnet, epidote, vesuvianite, diopside, tremolite and wollastonite. There is in addition some quartz, abundant carbonate and minerals such as pyrite, pyrrhotite, molybdenite, arsenopyrite and magnetite. Typical examples of these types of deposits are the Nickel Plate deposit at Hedley, British Columbia that is marked by abundant auriferous arsenopyrite, often in massive lenses, and the French deposit in the same area that is mainly a skarn zone with little arsenopyrite.

Skarn-type gold deposits commonly exhibit minor to major secondary alteration effects superimposed on the skarn.

Where these are present the pyroxene is frequently replaced by tremolite and actinolite, and there are developments of quartz, epidote, calcite, sericite, and chlorite or serpentine.

The chemistry of skarnification is well illustrated by the copper deposits near Whitehorse, Yukon that carry, however, only small amounts of gold and silver (0.25 oz Au/ton and 6 oz Ag/ton of concentrates). There, the relationships are exceptionally clear as shown in Figure 9. Further details of the geology are outlined by Kindle (1964).

The analyses (Table 44) and profiles (Fig. 10) show the normal relationships commonly observed during skarnification. As silica, alumina, iron, titania and manganese are introduced into the limestone, there is a moderate extraction of lime and a wholesale removal of carbon dioxide. MgO shows an erratic behaviour. Na_2O and K_2O are enriched only in the rocks near the granodiorite, and P_2O_5 exhibits an enrichment near the central part of the skarn zone. Water tends to be enriched in the skarn compared with the original limestone. Sulphur exhibits an erratic behaviour being concentrated, however, in the skarn adjacent to the orebody.

It will be noted that lithium tends to follow the major alkalis rather than magnesium as is common in some rocks. Rubidium follows potassium closely, and barium behaves in a similar manner. Strontium exhibits a mixed behaviour, following the major alkalis in the zone next to the granodiorite and calcium in the limestone.

Copper shows a marked increase as the orebody is approached, a feature also exhibited by silver, gold, mercury and arsenic.

Considering various ratios it is apparent that there are some consistencies. Approaching the orebody from the granodiorite the data in Table 44 show that the K_2O/Na_2O ratios increase and the SiO_2/CO_2 and SiO_2/total volatiles ratios exhibit a decrease, although for the last two an erratic behaviour is apparent along parts of the traverse. As the orebody is approached from the limestone side the K_2O/Na_2O ratios show no change, whereas the SiO_2/CO_2 and SiO_2/total volatiles ratios register an increase.

Veins, lodes, stockworks, mantos and bedded disseminated deposits

There are several types of these deposits as noted at the beginning of this chapter. Here we shall deal successively with those dominantly in intermediate and basic intrusive and extrusive rocks; those dominantly in intrusive and extrusive acidic (granitic) rocks; and those dominantly in sedimentary rocks.

Gold-quartz veins and silicified zones dominantly in intermediate and basic extrusive and intrusive rocks (Yellowknife type)

Deposits of this type commonly occur in volcanic terranes, the principal host rocks being andesites and basalts, now largely greenstones. Similar types of deposits also occur in syenite, dacite, granodiorite, monzonite, diorite, diabase and gabbro plugs or stocks in various terranes. Their alteration zones are similar and are included here.

Deposits of this type range in age from Precambrian or Tertiary. Characteristic examples of Precambrian age in Canada include the deposits of Yellowknife, Northwest Territories, Squall Lake, Manitoba; San Antonio, Manitoba; various deposits in the Red Lake area of Ontario; various deposits in the Timmins area of Ontario; the Kerr Addison deposit in the Larder Lake district of Ontario; the Cordova Mine in eastern Ontario near Marmora; and a number of deposits in western Quebec including Arntfield, Wasa Lake, Senator-Rouyn, Stadacona, East Malartic; and others. Elsewhere in the world Precambrian members of this type occur in Kalgoorlie and Coolgardie districts of Western Australia, in the Barberton district of South Africa and in the Kolar goldfields of India.

Deposits of Mesozoic age of this type are widespread in the Western Cordillera of North America. Here belong the great deposits of the Mother Lode of California; a number of deposits in British Columbia, including the Bralorne Mine; and a number of deposits in Alaska including some of the orebodies of the Alaska Juneau Gold Mine.

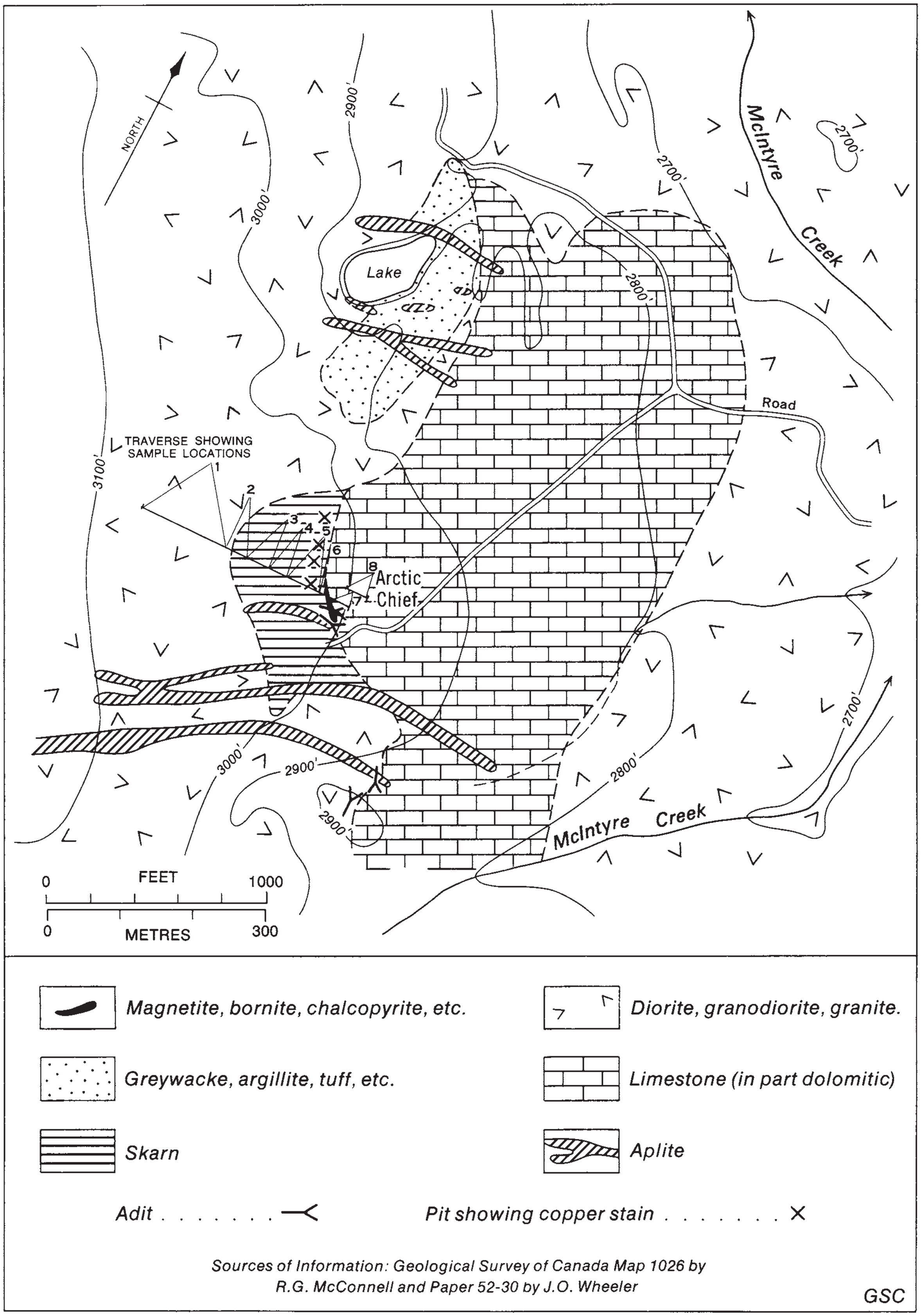
Tertiary deposits of this type are, likewise, widespread throughout the world occurring in Romania, Japan, New Zealand, Fiji, U.S.S.R., the western United States and elsewhere.

Yellowknife area, Northwest Territories (Precambrian: Archean age). The alteration zones associated with the Yellowknife gold deposits in the greenstone belt are typical examples of gold-quartz veins and silicified zones in intermediate to basic volcanic and igneous rocks. They have been described in detail by the writer (Boyle, 1961*a*). Only the significant facts need be considered here.

Three metamorphic facies characterize the Yellowknife Greenstone Belt, which is composed essentially of meta-andesite and meta-basalt flows and diorite dyke swarms. An amphibolite facies is developed adjacent to the western granodiorite-granite, which grades inward through an intermediate epidote amphibolite facies into a poorly defined greenschist facies. The deposits are quartz veins and silicified zones in great shear zones and subsidiary faults. The principal minerals in the veins and silicified zones are quartz, carbonates, pyrite, arsenopyrite, pyrrhotite, stibnite, sulphosalts, gold and aurostibite.

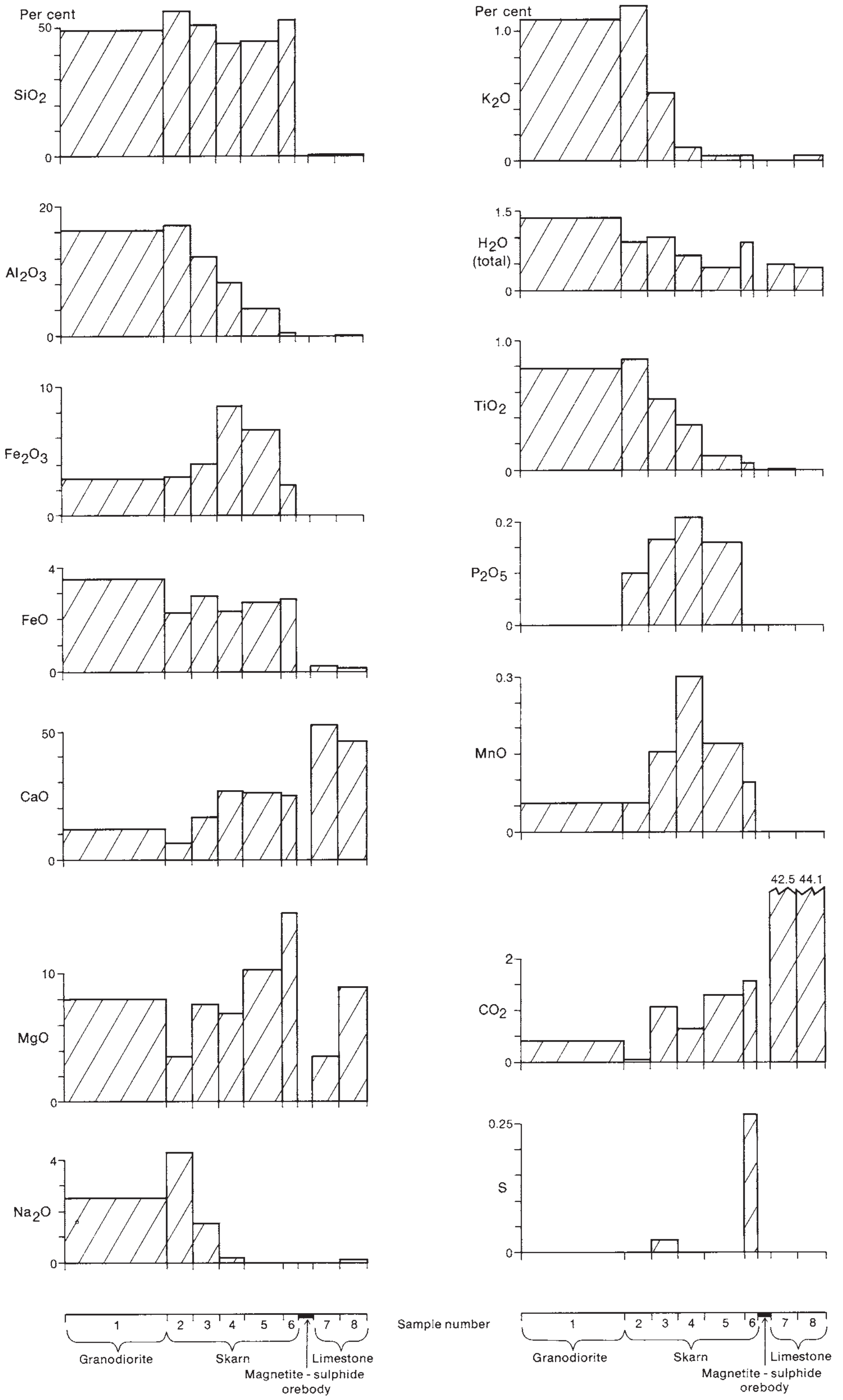
Most shear zones in the amphibolite facies of the greenstone belt contain quartz lenses and stringers, which are flanked by characteristic alteration zones. The wall rocks are predominantly amphibolites, containing hornblende, oligoclase-andesine, quartz, magnetite, sphene, ilmenite and small amounts of epidote, pyrite and pyrrhotite. These minerals are destroyed in the shear zones, and a weakly schistose aggregate of chlorite, albite, sericite and leucoxene is present. Adjacent to quartz lenses, the chlorite schist of the shear zones grades imperceptibly into a chlorite-albite-sericite schist containing quartz, leucoxene and/or sphene and small amounts of calcite. Pyrite, pyrrhotite and arsenopyrite are present and may make up 0.5 per cent of the schistose rock. The shear zones are rarely more than 3 ft wide, and the alteration zones adjacent to quartz lenses are 1 ft or so wide.

The rocks of the epidote amphibolite and greenschist facies are cut by the highly productive shear zones of four ore-bearing systems (Fig. 17). There is relatively little difference in the internal arrangement of the alteration haloes in these four systems, and the following description applies to all shear zones in these two facies.



Sources of Information: Geological Survey of Canada Map 1026 by R.G. McConnell and Paper 52-30 by J.O. Wheeler

Figure 9. Surface geology at the Arctic Chief Mine, Whitehorse Copper Belt, Yukon Territory.



For location of samples see Figure 9

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Figure 10. Profiles of elements along traverse across skarn, Arctic Chief Mine, Whitehorse Copper Belt, Yukon Territory (*see* Table 44).

Table 44. Analyses of rocks along traverse (Fig. 9) Whitehorse Copper (skarn) Belt, Whitehorse, Yukon*

Rock type	Granodiorite	Granodiorite in contact zone	Skarn	Skarn	Skarn	Skarn near ore	Limestone near ore	Limestone country rock
Sample number on traverse	1	2	3	4	5	6	7	8
				%				
SiO_2	49.6	57.8	50.9	44.2	45.8	51.3	0.81	0.16
Al_2O_3	16.3	17.8	12.2	8.7	4.4	0.89	0.00	0.08
Fe_2O_3	3.1	3.3	4.1	8.5	6.7	2.3	0.00	0.00
FeO	3.58	2.23	2.94	2.33	2.75	2.78	0.10	0.04
CaO	12.1	7.1	17.4	27.7	27.3	24.6	52.8	45.3
MgO	8.0	3.6	7.5	6.9	10.2	15.2	3.7	8.9
Na_2O	2.6	4.3	1.6	0.20	0.00	0.00	0.00	0.02
K_2O	1.1	1.2	0.52	0.10	0.02	0.02	0.00	0.02
H_2O (total)	1.42	0.90	1.0	0.66	0.44	0.84	0.48	0.42
TiO_2	0.79	0.85	0.57	0.37	0.10	0.05	0.01	0.00
P_2O_5	0.00	0.10	0.17	0.21	0.16	0.00	0.00	0.00
MnO	0.06	0.06	0.15	0.30	0.17	0.09	0.00	0.00
CO_2	0.48	0.06	1.1	0.68	1.28	1.56	42.50	44.10
S	nf	nf	0.02	nf	nf	0.27	nf	nf
C			0.04					
$O \equiv S$			0.01			0.11		
Total	99.1	99.3	100.2	100.9	99.3	99.8	100.4	99.0
				(ppm)				
Li	8	5	<1	<1	1	<1	<1	<1
Rb	24	23	24	3	<1	<1	<1	<1
Cs	<1	<1	<1	<1	<1	<1	<1	<1
Be	<2	<2	<2	<2	<2	<2	<2	<2
Sr	620	740	760	100	31	25	820	500
Ba	330	540	540	18	10	13	10	13
B	nf	nf	nf	<50	<50	nf	nf	nf
Sc	42	20	15	nf	nf	nf	nf	nf
U	0.3	0.8	1.1	2.8	1.7	1.0	1.4	1.9
Pb	4	7.5	4	<4	4	<4	<4	5
Cu	42	34	65	25	42	3380	140	9
Ag	<0.4	<0.4	<0.4	0.5	<0.4	0.6	<0.4	<0.4
Au	<0.005	<0.005	<0.005	<0.005	0.005	0.055	0.045	<0.005
Zn	63	50	52	49	60	47	17	10
Cd	<0.4	0.5	<0.4	<0.4	<0.4	<0.4	<0.4	<0.4
Hg (ppb)	127	113	293	170	45	637	488	428
Zr	60	72	150	120	57	nf	nf	nf
As	<6	<6	<6	<6	<6	<6	6	<6
Sb	<1	<1	<1	<1	<1	<1	<1	<1
Bi	nf	nf	nf	nf	nf	nf	nf	nf
V	210	230	240	200	140	60	nf	nf
Se	<1	<1	<1	1	<1	<1	<1	<1
Te	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Cr	200	27	17	nf	nf	nf	nf	nf
Mo	1.2	1.2	0.7	1.0	0.5	0.5	0.5	0.5
W	2	3	<2	<2	<2	<2	<2	<2
Co	31	18	18	14	14.5	17.5	<2	<2
Ni	56	17	17.5	16	18.5	21	8	8.5
Pt(ppb)	<15	<15	<15	<15	<15	<15	<15	<15
Pd(ppb)	<2	<2	<2	<2	<2	<2	2	<2
F	400	500	650	300	425	300	650	350
Cl	600	350	400	300	250	300	<100	150
Ratios								
K_2O/Na_2O	0.42	0.28	0.33	0.50	>4	>4	1	1
SiO_2/CO_2	103.3	963.3	46.3	65.0	35.78	32.88	0.02	0.004
SiO_2/H_2O+CO_2+S	26.1	60.2	24.0	33.0	26.6	19.2	0.02	0.004

Note: nf–not found.

*For location of samples *see* Figure 9. Samples comprised a large aggregate of chip samples across a 10 ft width for distance noted along traverse.

Table 45. Phases of alteration in the shear zones of the Giant-Campbell, Con, Negus-Rycon and Crestaurum systems, Yellowknife, Northwest Territories

Phase	Minerals present (in order of relative abundance)	Remarks
Country rock	Fibrous amphibole, oligoclase, epidote, quartz, magnetite, leucoxene, sphene, chlorite, carbonates, pyrite, pyrrhotite, apatite, minor reticulating epidote-carbonate veinlets	Massive to slightly schistose greenstone country rock
1.	Chlorite, fibrous amphibole, oligoclase, epidote, quartz, magnetite, ilmenite, leucoxene, sphene, carbonates, pyrite, pyrrhotite, apatite, reticulating epidote-carbonate veinlets, hematite on slips in some places	Wall rock adjacent to shear zones; rock is weakly schistose
2.	Chlorite, albite, ankerite, quartz, leucoxene, pyrite, small amounts of fibrous amphibole, apatite and epidote in some places, pyrrhotite locally, rare reticulating epidote-carbonate veinlets	Shear zone; chlorite schist; marked foliation
3.	Chlorite, ankerite, albite, quartz, leucoxene, pyrite, colourless to faintly greenish mica, rare occurrences of tourmaline, apatite and pyrrhotite	Shear zone; chlorite-carbonate schist; strong foliation
4.	Ankerite, chlorite, sericite, quartz, albite, leucoxene, pyrite, arsenopyrite, rare occurrences of tourmaline and apatite	Shear zone; carbonate-chlorite-sericite schist; strong foliation
5.	Ankerite, sericite, quartz, chlorite, pyrite, arsenopyrite, rutile needles, rare occurrences of tourmaline and apatite	Shear zone; carbonate-sericite schist; strong foliation
6.	Quartz, sericite, ankerite, pyrite, arsenopyrite, sulphosalts, gold, sphalerite, etc., rutile needles, rare occurrences of tourmaline	Mineralized zones; orebodies in some cases
Quartz bodies	Quartz, arsenopyrite, pyrite, sulphosalts, sericite, ankerite, gold, rare occurrences of tourmaline and apatite, scheelite in some quartz lenses	Quartz lenses and veins; orebodies

In most of the shear zones of the four systems (Giant-Campbell, Con, Negus-Rycon and Crestaurum) the six alteration phases listed in Table 45 can be recognized. The widths of the phases vary extensively throughout the systems; in some places individual phases may be tens and even hundreds of feet wide. All phases are not necessarily present within a shear zone. All shear zones are marked by a development of phases 1 and 2 and locally by a mild development of phase 3. Where orebodies and mineralized zones are present, all phases are generally present, but some orebodies lack an adjacent pronounced sericite-carbonate phase.

The location of the more intensely altered phases (3–6) of the shear zone is controlled in most places by the same structural features that have localized the quartz veins and lenses, namely, shear-zone junctures and flexures and dragged parts of schist zones.

The country rocks are predominantly epidote amphibolites. The amphibolites contain fibrous amphibole (actinolite), albite-oligoclase, epidote, quartz, magnetite, ilmenite, leucoxene, chlorite, carbonate, pyrite and pyrrhotite in that order of abundance. These minerals are highly intergrown with one another, and the rock has a poorly developed schistose texture in thin sections. In hand specimens the rock is massive and breaks with a blocky to irregular fracture.

Phase 1 marks a transition between the epidote amphibolite country rock and the shear zones, and only a slight schistosity has been impressed on the rocks. The main feature of this phase is the occurrence of reticulating pinkish buff and pistachio-green epidote-carbonate veinlets. In most occurrences these veinlets contain a dense intergrowth of epidote, calcite or ankerite, quartz, albite, tremolite, leucoxene, chlorite, hematite and pyrite. In other occurrences quartz-carbonate stringers form a central core flanked by a narrow epidote-carbonate alteration zone containing the minerals listed above. Seams and joints coated with hematite occur in this phase in many places especially in the shear zones of the Giant System.

Phase 2 constitutes the chlorite schist phase of the shear zones. The rock is dark green and is highly foliated both in hand specimens and thin sections. Constituent minerals include, in order of abundance, green chlorite, albite, ankerite, quartz, leucoxene, pyrite and epidote. In some places a few small reticulating carbonate-epidote veinlets are present. The albite and quartz commonly occur in small elongated lenses and in bands in the highly foliated chlorite masses. The leucoxene occurs in small buff to white, optically opaque masses with a linear arrangement along the foliated chlorite masses. Narrow quartz and carbonate veinlets cut across the schistosity in most specimens.

Phase 2 grades imperceptibly by increase in ankerite into the chlorite-carbonate schist of phase 3. In thin sections the gradation is marked by a bleaching of part of the chlorite to give a colourless to faintly greenish mica that has low first order interference colours and contains small leucoxene knots. The leucoxene is clearer than in the chlorite schist, and in some thin sections small diffuse crystals of rutile can be discerned in the irregular leucoxene masses. Albite, quartz and pyrite are generally present, and in a few localities apatite and small amounts of tourmaline may occur. In thin sections the rock shows a banded structure. Some bands contain green chlorite, light green mica and albite. Locally ankerite occurs in small crenulations and seams, which cut the bands. Quartz is commonly present in augenlike masses around pyrite crystals or in seams and veinlets parallel to or transecting the bands of other minerals. The rock is green to greenish buff in colour and is strongly foliated in hand specimens and thin sections.

In the vicinity of quartz lenses and mineralized zones the chlorite-carbonate schist phase grades, by increase of ankerite, sericite and quartz, into the carbonate-chlorite-sericite schist of phase 4. This phase in turn grades, by increase in sericite, carbonate and quartz and decrease in chlorite, into the carbonate-sericite schist of phase 5. The latter grades into either mineralized zones (phase 6) or quartz veins and lenses, by increase in quartz and sulphides.

The macroscopic and microscopic features of phases 4, 5 and 6 are nearly the same in all occurrences. The rock is grey to buff and highly foliated in hand specimens and thin sections. Mashing and extreme contortion of the schist occurs in most shear zones, especially in those of the Giant-Campbell System. The rock contains variable amounts of ankerite, sericite, chlorite, quartz, pyrite, arsenopyrite and leucoxene depending upon the phase in which it occurs. In phases 4 and 5 the minerals occur in bands in some localities; in others, especially in parts of the Negus-Rycon System, all minerals occur as a dense intergrowth. Toward the mineralized zones and quartz bodies there is a definite increase in pyrite and arsenopyrite. These minerals occur principally in sericite bands, but may be scattered throughout the general groundmass. Trains of leucoxene masses, in which rutile needles are readily distinguishable, occur along all the sericite bands. The leucoxene is a marked feature of these phases of alteration and gives the rock its distinctive buff colour. Small quartz and carbonate veinlets intersect the highly altered phases throughout their extent.

The alteration phases are general in most of the shear zones of the four major systems. In a few shear zones, however, there are a few differences, mainly in the textures of the zones. In these shear zones alteration phases 3 to 6, are compressed into a zone rarely more than 1 ft wide. This composite zone consists of a dense intergrowth of microcrystalline ankerite, bleached chlorite, quartz, albite, sericite, chlorite, trains and disseminated masses of leucoxene and abundant pyrite and arsenopyrite. The rock of this zone is only slightly foliated and appears as a narrow buff to grey-coloured, dykelike zone adjacent to the quartz lenses. The transition to the chlorite schist phase, which also shows only a limited degree of foliation, is sharp. In many places there is a zoning of the sulphides outward from the quartz. Arsenopyrite occurs adjacent to the quartz veins, pyrite farther out but within the highly altered phase and pyrrhotite in the chlorite schist phase. In all occurrences small quartz-carbonate and albite-quartz veinlets ramify through the highly altered phase.

Chemical analyses have been made of the typical alteration phases in the shear zones of the greenstone belt where they intersect epidote amphibolite rocks.

Tables 46 and 47 record the percentage of each constituent, the adjusted percentage after volume calculations, the gains and losses and the percentage gains and losses for samples taken across well-defined alteration zones in the two shear-zone systems of the greenstone belt. Table 48 shows the results of analyses of large composite samples from the two major phases of alteration in shear zones that cut greenstones. These samples were selected with great care from all shear zones investigated and probably give the best data on the general overall trend of the chemical changes.

The alteration zoning in the Con, Negus-Rycon and Giant-Campbell systems was studied in detail by thin sections and chemical and spectographic analyses. The alteration features of these systems, while slightly different in a few respects from those of other systems, are typical and illustrate the trend in all shear zones cutting the greenstones.

For purposes of discussion the various phases given in Table 45 may be grouped into three general phases – the country rock (greenstone), chlorite and chlorite-carbonate schist phase and the carbonate-sericite schist phase.

The microscope reveals that the amphibole of the country rock was altered first to chlorite and ankerite; in the more intense phases the chlorite in turn was altered to sericite. The plagioclase may have lost calcium to form albite in the chlorite phase, but it has been generally obliterated in the sericite phase, and sericite and ankerite have formed at its expense. Epidote has been altered to chlorite or to carbonate depending upon the intensity of alteration. Ilmenite, magnetite and sphene have been generally obliterated, and pyrite, arsenopyrite, rutile and leucoxene have formed from some of the components of these minerals. Quartz and carbonate minerals have formed throughout the highly altered phases.

It is probable that the carbon dioxide, water and sulphur were derived from the greenstone country rocks, and that these compounds diffused into the dilatant shear-zone systems (Boyle, 1959). Here they reacted with the minerals present producing new minerals stable under the existing conditions. To maintain the equilibrium, various chemical exchanges, as shown by the profiles in Figures 11, 12 and 13, have taken place. For purposes of discussion let us examine the results as shown by the profiles drawn from the analyses of the composite samples (Fig. 13). Local variations will be reflected in the profiles from the individual shear zones.

The profile for SiO_2 shows a marked decrease in the chlorite-carbonate and sericite schist phases of the shear zones compared with the greenstone. This decrease is attended by an increase in CO_2 in both phases, by H_2O in the chlorite-carbonate phase and by S in the carbonate-sericite phase. This suggests that these gaseous components displaced the liberated SiO_2 to maintain the chemical equilibrium. The profiles from all shear zones show similar features and we may, therefore, conclude that as the volatiles were added to the system, silica was liberated and migrated into dilatant zones to form the quartz veins and lenses. More will be said about this in the sections to follow and in the section on the origin of gold deposits in this chapter.

The content of Al_2O_3 in the composite samples shows a decrease in the chlorite-carbonate phase and an increase in the carbonate-sericite phase as compared with the greenstone. Similar features are shown by the profile of the Negus-Rycon System, but in the Campbell System the Al_2O_3 content of the carbonate-sericite phase is lower than both the greenstone and chlorite-carbonate phase. This anomaly can perhaps be explained by the degree of carbonatization. The Campbell System shows much higher percentage gains in CO_2 than the Negus-Rycon System, and more carbonate has formed at the expense of the aluminous silicates. Hence, the greater migration of Al_2O_3 to maintain the chemical equilibrium.

The Fe_2O_3, FeO, CaO, MgO, TiO_2 and MnO contents of the composite samples show individual trends in the alteration phases, but their combined content shows an overall decrease in both alteration phases compared to the greenstone. This tendency is also shown by the analyses from the individual shear zones and appears to be general.

The Na_2O content decreases consistently in the two alteration phases compared with the greenstone. This loss of soda is also shown by the analyses from the two specific shear-zone systems.

Compared with the greenstone, the K_2O content of the composite samples is relatively constant in the chlorite-carbonate phase but increases many times in the carbonate-sericite phase. In specific shear zones the K_2O content may

Table 46. Chemical changes produced by alteration of greenstone, Negus-Rycon System, Yellowknife, Northwest Territories

Constituent	YC-16*	YC-17†	Adjusted§	Gains and losses in constituents	Percentage gains and losses	YC-16*	YC-18‡	Adjusted§	Gains and losses in constituents	Percentage gains and losses
		(%)					(%)			
SiO_2	49.18	45.40	43.54	–5.64	–11.45	49.18	34.96	35.30	–13.88	–28.20
Al_2O_3	10.59	7.35	7.05	–3.54	–33.50	10.59	12.21	12.33	+1.74	+16.45
Fe_2O_3	7.20	3.56	3.41	–3.79	–52.65	7.20	3.01	3.04	–4.16	–57.80
FeO	9.87	9.16	8.78	–1.09	–11.05	9.87	8.93	9.02	–0.85	–8.60
CaO	11.01	10.99	10.54	–0.47	–4.25	11.01	10.42	10.52	–0.49	–4.45
MgO	5.63	4.18	4.01	–1.62	–28.80	5.63	4.40	4.44	–1.19	–21.16
Na_2O	1.16	0.50	0.48	–0.68	–58.75	1.16	1.11	1.12	–0.04	–3.44
K_2O	0.24	1.02	0.98	+0.74	+308.00	0.24	2.48	2.50	+2.26	+941.00
H_2O^+	1.46	3.26	3.13	+1.67	+114.50	1.46	0.80	0.81	–0.65	–44.50
H_2O^-	0.07	0.14	0.13	–	–	0.07	0.31	0.31	–	–
TiO_2	0.84	1.05	1.01	+0.17	+20.20	0.84	1.79	1.81	+0.97	+115.75
P_2O_5	0.18	0.38	0.36	+0.18	+100.00	0.18	0.70	0.71	+0.53	+294.50
MnO	0.22	0.11	0.10	–0.12	–55.50	0.22	0.08	0.08	–0.14	–63.60
CO_2	1.39	9.56	9.17	+7.78	+560.00	1.39	12.13	12.30	+10.91	+785.00
S	0.85	2.17	2.08	+1.23	+145.00	0.85	6.47	6.55	+5.70	+670.00
As_2O_3	trace	1.57	1.50	+1.50	–	trace	1.93	1.95	+1.95	–
Total	99.89	100.30	–	–	–	99.89	101.73	–	–	–
Specific gravity	2.97	2.85	–	–	–	2.97	3.01	–	–	–

*YC-16–greenstone, chip sample across 80 ft, 11th level, Negus Mine, Negus-Rycon System.
†YC-17–chlorite and chlorite-carbonate schist, chip and channel sample across 2 ft, 11th level, Negus Mine, Negus-Rycon System.
‡YC-18–carbonate-chlorite and carbonate-sericite schist, chip and channel sample across 1 ft, 11th level, Negus Mine, Negus-Rycon System.
§–Adjusted % = percentages of YC-17 and YC-18 multiplied by the factors 2.85/2.97 and 3.01/2.97 respectively, to reduce to a common volume.

Table 47. Chemical changes produced by alteration of greenstone, Campbell System, Yellowknife, Northwest Territories

Constituent	YC-19*	YC-20†	Adjusted§	Gains and losses in constituents	Percentage gains and losses	YC-19*	YC-21‡	Adjusted§	Gains and losses in constituents	Percentage gains and losses
		(%)					(%)			
SiO_2	51.53	43.91	40.92	–10.61	–20.59	51.53	49.29	49.29	–2.24	–4.35
Al_2O_3	16.31	14.72	13.71	– 2.60	–15.90	16.31	13.10	13.10	–3.21	–19.65
Fe_2O_3	0.94	0.30	0.28	– 0.66	–70.10	0.94	1.21	1.21	+0.27	+28.75
FeO	9.65	6.87	6.40	– 3.25	–33.70	9.65	5.67	5.67	–3.98	–41.25
CaO	8.59	9.43	8.78	+0.19	+2.22	8.59	7.99	7.99	–0.60	–7.00
MgO	6.23	7.69	7.17	+0.94	+15.10	6.23	3.81	3.81	–2.42	–38.95
Na_2O	2.49	1.63	1.52	– 0.97	–38.90	2.49	0.33	0.33	–2.16	–86.60
K_2O	0.11	0.70	0.65	+0.54	+491.00	0.11	1.59	1.59	+1.48	+1345.50
H_2O^+	2.11	3.55	3.31	+1.20	+56.80	2.11	1.45	1.45	–0.66	–31.30
H_2O^-	0.10	0.46	0.43	–	–	0.10	0.10	0.10	–	–
TiO_2	0.84	0.58	0.54	– 0.30	–35.75	0.84	0.26	0.26	–0.58	–69.00
P_2O_5	0.22	0.33	0.31	+0.09	+40.95	0.22	0.14	0.14	–0.07	–31.80
MnO	0.16	0.22	0.20	+0.04	+25.00	0.16	0.08	0.08	–0.08	–50.00
CO_2	0.55	9.60	8.95	+8.40	+1529.00	0.55	10.48	10.48	+9.93	+1800.00
S	0.28	0.43	0.40	+0.12	+42.80	0.28	3.67	3.67	+3.39	+1210.00
As_2O_3	–	–	–	–	–	–	2.87	2.87	+2.87	–
Total	100.11	100.42	–	–	–	100.11	102.04	–	–	–
Specific gravity	2.95	2.75	–	–	–	2.95	2.94	–	–	–

*YC-19–Greenstone wall rock, chip sample across 250 ft, 13th level, Negus Mine, Campbell System.
†YC-20–Chlorite and chlorite-carbonate schist, chip sample across 70 ft, 13th level, Negus Mine, Campbell System.
‡YC-21–Carbonate-chlorite and carbonate-sericite schist, quartz stringers and small lenses. Chip and channel sample across 8 ft, 13th level, Negus Mine, Campbell System.
§Adjusted % = percentages of YC-20 and YC-21 multiplied by the factors 2.75/2.95 and 2.94/2.95 respectively, to reduce to a common volume.

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Table 48. Chemical changes produced by alteration of greenstone, composite samples of all shear-zone systems, Yellowknife, Northwest Territories

Constituent	A-76*	A-251†	Adjusted§	Gains and losses in constituents	Percentage gains and losses	A-76*	A-250‡	Adjusted§	Gains and losses in constituents	Percentage gains and losses
		(%)					(%)			
SiO_2	50.45	40.36	37.12	–13.33	–26.42	50.45	38.19	38.30	–12.15	–24.08
Al_2O_3	13.96	12.87	11.84	–2.12	–15.19	13.96	16.26	16.31	+2.35	+16.83
Fe_2O_3	2.00	1.06	0.97	–1.03	–51.50	2.00	0.38	0.38	–1.62	–81.00
FeO	9.61	12.00	11.04	+1.43	+14.88	9.61	3.49	3.50	–6.11	–63.58
CaO	10.23	8.94	8.22	–2.01	–19.65	10.23	11.02	11.05	+0.82	+8.02
MgO	6.53	8.43	7.75	+1.22	+18.68	6.53	5.77	5.79	–0.74	–11.33
Na_2O	1.85	0.90	0.83	–1.02	–55.14	1.85	0.29	0.29	–1.56	–84.32
K_2O	0.39	0.41	0.38	–0.01	–2.56	0.39	2.82	2.83	+2.44	+622.64
H_2O^+	2.36	5.20	4.78	+2.42	+102.54	2.36	1.16	1.16	–1.20	–50.85
H_2O^-	0.11	0.13	0.12	+0.01	+9.09	0.11	0.10	0.10	–0.01	–9.09
TiO_2	1.02	1.05	0.97	–0.05	–4.90	1.02	0.82	0.82	–0.20	–19.61
P_2O_5	0.13	0.11	0.10	–0.03	–23.08	0.13	0.21	0.21	+0.08	+61.54
MnO	0.21	0.22	0.20	–0.01	–4.76	0.21	0.17	0.17	–0.04	–19.05
CO_2	0.68	8.03	7.39	+6.71	+986.76	0.68	15.57	15.62	+14.94	+2197.06
S	0.22	0.12	0.11	–0.11	–50.00	0.22	3.26	3.27	+3.05	+1386.36
Cl	0.02	0.00	0.00	–0.02	–100.00	0.02	0.01	0.01	–0.01	–50.00
Cr_2O_3	0.03	0.03	0.03	0.00	0.00	0.03	0.00	0.00	–0.03	–100.00
C	0.04	0.12	0.11	+0.07	+175.00	0.04	0.04	0.04	0.00	0.00
Total	99.84	99.98				99.84	99.56			
Less O≡S,Cl	0.10	0.05				0.10	1.22			
Net total	99.74	99.93				99.74	98.34			
Specific gravity	2.99	2.75				2.99	3.00			
				(ppm)						
Li	16	49				16	12			
Rb	11	12				11	106			
Cs	0.3	0.4				0.3	3.9			
B	15	93				15	150			
As	2	74				2	6900			
Sb	<1	26				<1	23			
Au	0.008	0.017				0.008	0.632			
Ag	0.7	0.256				0.7	1.13			
Ratios										
K_2O/Na_2O	0.21	0.46				0.21	9.72			
SiO_2/CO_2	74.19	5.03				74.19	2.45			
SiO_2/H_2O+CO_2+S	15.48	3.02				15.48	1.85			
Au/Ag	0.01	0.06				0.01	0.56			

*A-76–composite sample from epidote-amphibolite facies (greenstone country rock).

†A-251–composite sample of chlorite-carbonate schist of shear zones. Widths vary from 1–70 ft or more.

‡A-250–composite sample of carbonate-sericite schist of shear zones. Widths vary from 0.5 to 10 ft or more.

§Adjusted%=percentages of A-251 and A-250 multiplied by the factors 2.75/2.99 and 3.00/2.99 respectively, to reduce to a common volume.

increase significantly in the chlorite-carbonate phase.

The profiles of H_2O as shown by the analyses of both the composite samples and those from individual systems behave consistently. The water content increases in the chlorite-carbonate phase and decreases in the carbonate-sericite phase compared to the greenstone.

In all cases the profiles for CO_2 clearly indicate an increase in this constituent in all the alteration phases of the shear zones as compared with the greenstone. The greatest amounts are present in the carbonate-sericite phase with lesser amounts in the chlorite-carbonate phase.

The sulphur profiles of the alteration phases of the shear zones provide some interesting data on the origin of the sulphides in the orebodies and carbonate-sericite phase. As shown by the analyses of composite samples, the content of sulphur is less in the chlorite-carbonate phase than in the greenstone. In the carbonate-sericite phase the content is high, a feature that is common to all shear zones. Considering the profiles of the two specific shear-zone systems, however, it will be noted that the sulphur content is higher in both phases of the shear zones than in the greenstones. This apparent anomaly in the two results may be due to different sampling procedures. In the case of the individual shear zones, continuous samples were taken across the shear zones. Since the chlorite-carbonate zones always contain small seams of carbonate-sericite-pyrite schist these were unavoidably included with the chlorite-carbonate schist samples. In other words no separation on strictly petrographic grounds was made. In the case of the composite samples petrographic control was rigidly adhered to, and the samples of the two phases of alteration were prepared in such a way as to exclude mutual contamination. It is evident from the results of the composite samples that where chlorite-carbonate schist was formed from greenstone the process led to a decrease in the sulphur content of the rock. The liberated sulphur probably migrated together with other components into the carbonate-sericite phase or to

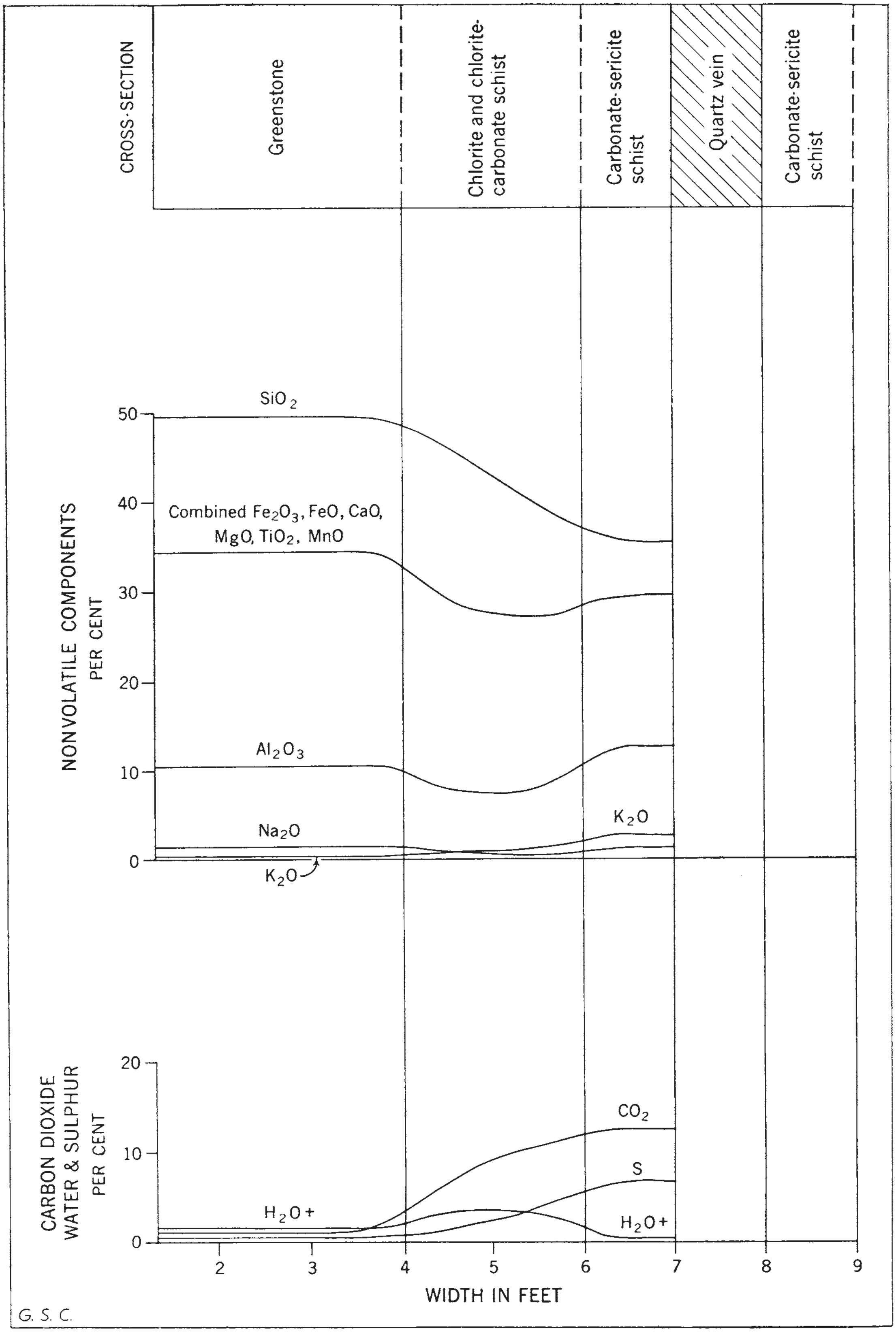

Figure 11. Chemical changes produced by alteration of greenstone, Negus-Rycon System, Yellowknife, Northwest Territories (*see* Table 46).

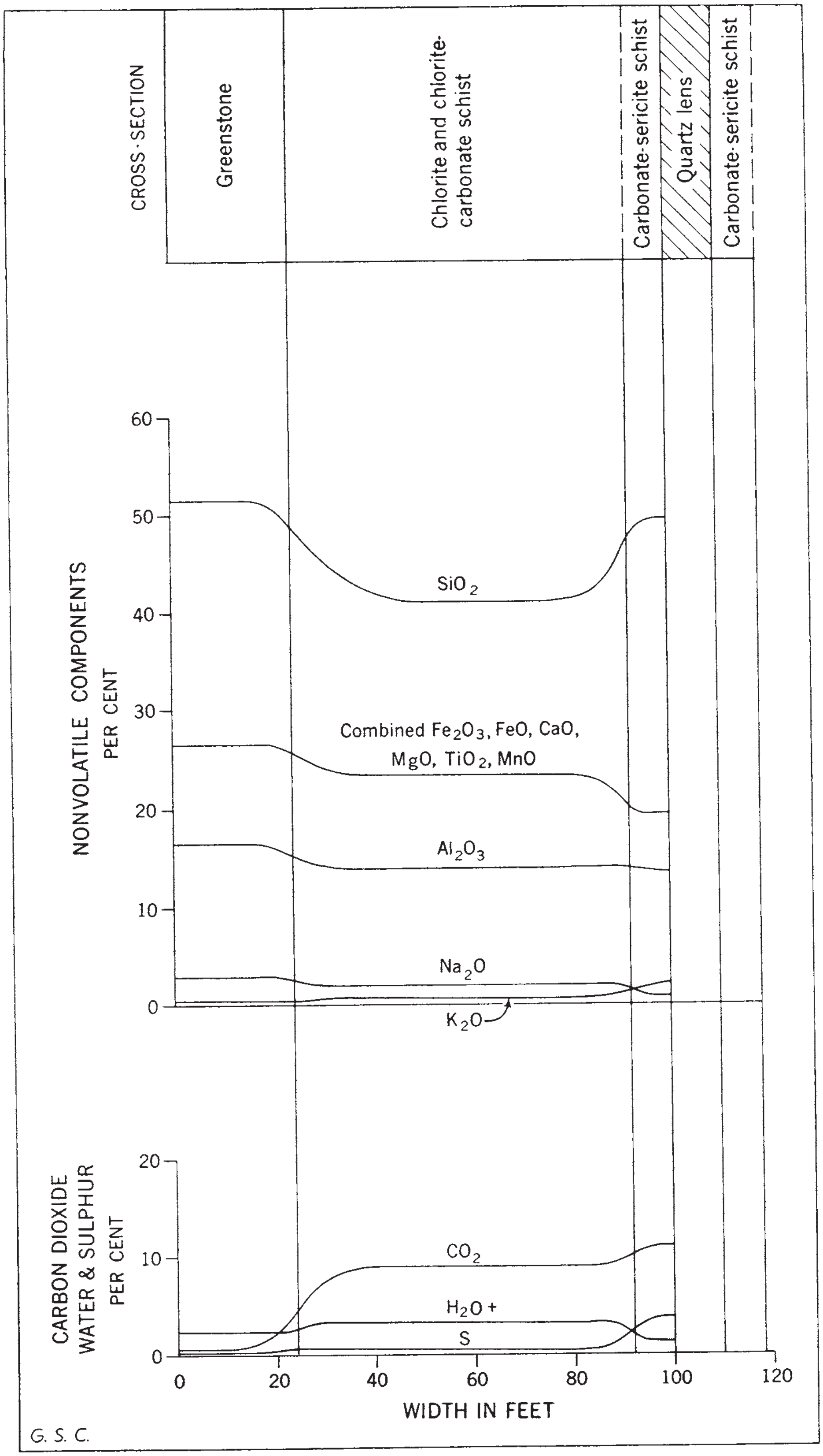

Figure 12. Chemical changes produced by alteration of greenstone, Campbell System, Yellowknife, Northwest Territories (*see* Table 47).

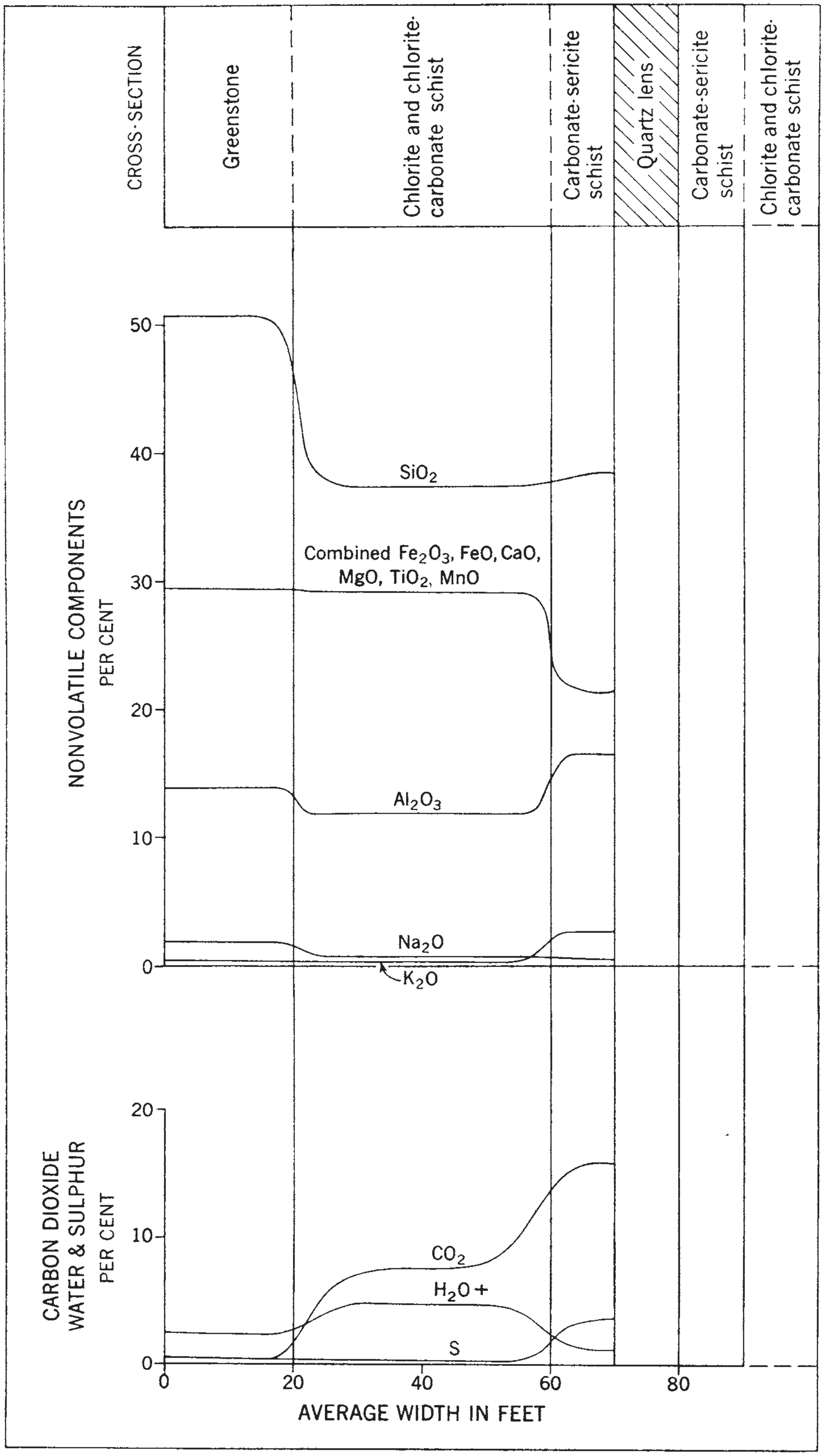

Figure 13. Chemical changes produced by alteration of greenstone, composite samples from all shear zones, Yellowknife, Northwest Territories (*see* Table 48).

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dilatant zones where it was precipitated as pyrite and other sulphides. This concept is amplified further in the section on origin of gold deposits.

To summarize the chemical features displayed by the profiles, it can be said that the principal agents responsible for the alteration were carbon dioxide and water, and to a lesser extent sulphur and arsenic. These volatiles reacted differently with the various mineral constituents of the greenstone rocks, and the alteration minerals formed reflect the chemical equilibrium attained under the conditions of pressure, temperature and concentration that prevailed during the formation of the shear zones. As carbon dioxide and water were added, silica was abstracted together with some iron, calcium, magnesium, titanium and manganese. Soda was leached from all alteration phases, and potash was enriched in the sericite phase. Sulphur was evidently mobilized in the chlorite-carbonate phase and migrated into the carbonate-sericite phase or into the site of the quartz lenses.

The mineral transformations and elemental migrations inferred from thin sections and chemical and spectographic analyses provide much data on the geochemistry and relative mobilities of the elements during the alteration processes. These are interpreted in the following sections according to well-established crystallochemical principles.

The amphiboles of the greenstone in the presence of CO_2 and H_2O have yielded either ankerite or chlorite or both depending upon the concentration of the two volatiles. To form chlorite the elemental constituents of the amphibole must have undergone a major structural rearrangement. During this process some of the Mg, Fe, Mn, Al_2O_3 and SiO_2 was bound by OH into the chlorite structure. The Ca and the remainder of the Fe, Mg and Mn were liberated and bound by CO_2 into the ankerite structure. The K and Na contained in the original amphibole were liberated during the process.

In the more highly carbonated parts of the shear zones the process has gone further, and the chlorite was attacked by the CO_2, and its Mg, Fe and Mn were bound into ankerite. This has liberated SiO_2 and Al_2O_3.

The plagioclase has undergone a similar alteration – its Ca content was bound into ankerite, and the K, Na, Al_2O_3 and SiO_2 formed albite in certain circumstances or migrated. In the same manner the Ca, Fe, Mn, Al_2O_3 and SiO_2 of the epidote minerals were incorporated into chlorite that was ultimately attacked by CO_2 to form ankerite with the liberation of SiO_2 and Al_2O_3.

Sulphur and arsenic diffusing through the shear zones have bound some iron liberated by the alteration of amphibole, chlorite and epidote into pyrite and arsenopyrite. Polished sections also show that the pyrite and arsenopyrite contain irregular unreplaced nuclei of magnetite and ilmenite suggesting that the iron in these minerals was also bound by sulphur and arsenic. Titanium was liberated during the alteration of the magnetite and ilmenite, the carbonatization of the amphibole and chlorite and the sericitization of the chlorite. This element was not readily accommodated in the carbonate, sericite or sulphide structures and hence formed an independent mineral phase, which now appears as irregular white leucoxene patches or aggregates of yellow rutile needles.

Potassium is enriched in the shear zones especially in the carbonate-sericite phase, adjacent to quartz lenses. It is often assumed that such a potash metasomatism is due to the introduction of potassium by magmatic solutions. This assumption neglects the pertinent facts that a ready source of potassium exists in the greenstones and that the element has a high mobility where differential pressure and shearing prevails and where water and carbon dioxide are present. The greenstone contains an average content of 0.25 per cent K_2O, held principally in the plagioclase and amphiboles. During the carbonatization and hydration of these minerals, the K^+ was liberated because large amounts could not be readily accommodated in the chlorite or carbonate structures. In the shear zones enormous masses of rock have been carbonatized and hydrated, and it follows that large amounts of potassium must have been set free.

Potassium shows large percentage gains in most of the alteration phases and is strongly enriched in the sericite schist adjacent to quartz lenses. From thin section studies it is apparent that the sericite is formed at the expense of both chlorite and plagioclase. These observations taken together with the chemical considerations discussed above suggest that the geochemical history of potassium during the alteration processes was as follows:

1. Release as K^+ or as a hydrated ion from its initial host minerals such as plagioclase and amphibole during carbonatization and hydration.

2. Diffusion of K^+ ions from zones of intense shearing into zones of lower pressure where reactions with chlorite and plagioclase or combination with alumina and silica took place to form sericite.

Sodium is bound principally in the plagioclase, but small amounts are also present in the amphiboles. During the carbonatization of these two minerals most of the sodium was liberated. Recombination may have taken place with alumina and silica to form albite locally, but much sodium has been leached and probably migrated to higher levels or was ultimately dispersed at the surface.

The percentage gains and losses for sodium are lower than for potassium, suggesting that sodium has the lower mobility of the two elements.

Alumina is fixed in the plagioclase, amphibole and epidote of the greenstone. During alteration of these minerals the alumina was redistributed among the chlorite, plagioclase and sericite of the alteration zones. Some parts of the shear zones are leached and others enriched, but the percentage gains and losses are low, suggesting that Al_2O_3 had a relatively low mobility during the alteration processes.

During the alteration of the greenstone most of its Ca, Mg, Mn and Fe content has been bound by carbon dioxide into ankerite; some iron has been bound by sulphur and arsenic into pyrite and arsenopyrite. The remainder of this group of elements, as shown by profiles of their combined oxides, has been leached suggesting migration into low-pressure zones such as the vein sites. There, much of the Ca, Mg, Mn and Fe was bound by CO_2, S and As into the ankerite, pyrite and arsenopyrite of the quartz lenses. Some of these elements, however, may have migrated upward along the shear zones and were dispersed at the surface.

The behaviour of a number of trace elements in the alteration zones in the deposits in greenstones at Yellowknife has been discussed previously in the section on associated elements. Of particular interest (Table 48) is the behaviour of Li, Rb, Cs, B, As, Sb, Au and Ag.

Lithium tends to follow magnesium, rather than the alkalis, and there is no increase in the element as the veins are approached, the largest amounts of lithium being present in the chlorite schists rather than in the sericite schists. Rubidium and cesium follow potassium and are enriched consistently as the auriferous veins are approached. Boron, arsenic, antimony, gold and silver, likewise, increase as the veins are approached.

Regarding ratios, it will be noted that there is a marked increase in the K_2O/Na_2O ratios and consistent and marked decreases in the SiO_2/CO_2 and SiO_2/total volatiles ratios as auriferous mineralization is approached. Similarly there is a marked increase in the Au/Ag ratio. These combined features are useful in predicting proximity to ore ahead of the bit during drilling as suggested by the writer in another paper (Boyle, 1974*b*).

Kirkland Lake, Ontario (Precambrian: Archean age). A number of gold deposits in the Kirkland Lake area occur in fracture zones that transect syenite porphyry. The wall-rock alteration attending these deposits has been examined by a number of investigators and is summarized by Thomson (1950) as follows:

> Wall-rock alteration has had a two-fold effect in that the original mineral constituents have been largely obliterated and at the same time a colour change has taken place in the syenite rock. The disappearance of the granitoid texture in the intrusives is the result of rock movement, whereas the colour change is produced by hydrothermal alteration.
>
> The rock adjacent to a vein-fault in the intrusives is changed from a massive holocrystalline rock to a banded, brecciated, or streaky variety. This may be reddened, bleached, or silicified, or there may be a mixture of all phases. The cherty-looking, silicified material has undergone the most complete granulation. Greenish-coloured alteration is prominent along some of the branch veins in the Teck-Hughes mine and certain veins in the sediments in the Sylvanite and Toburn mines. Much of the very pale green alteration is due to sericitization, but in a few places deep-green chrome mica (fuchsite) is developed over areas seldom more than an inch in diameter.
>
> Microscopic study shows that the crystals are first cracked or sheared along parallel lines, then progressively broken, granulated, and pulverized, depending upon the amount of alteration involved. Chlorite, sericite, and leucoxene have developed along narrow seams in the rock, and carbonate minerals and secondary quartz and pyrite have been introduced. The fine-grained bleached rock thus produced has often been further shattered to form a breccia, with one type of alteration embedded in a slightly different phase. Even this late breccia shows later fracturing. The resulting product is called mylonite in the camp. It is most commonly found along the stronger vein faults. Sometimes the mylonite bands have sharply defined contacts and resemble dikes or dikelets in appearance. The widths of the mylonite zone vary greatly and may be only a few inches or many feet.
>
> Microscopic examination of the mylonite shows that it is a microbreccia with a cataclastic structure. Where it has been formed by the alteration of syenite porphyry, the original feldspar phenocrysts may be seen in all stages of fracturing, slicing, and granulation. Sericite and chlorite have been developed along the fracture planes. In many thin sections secondary carbonates (chiefly iron-bearing dolomite) make up about half of the mineral constituents; there is also much secondary quartz and some pryite crystals. The colour is due to the carbonates, ferric oxide, and leucoxene.
>
> Carbonatization may affect large areas of rock and is not necessarily associated with the ore. It may be observed in the vicinity of any slip, whether pre-ore or post-ore, and the extent of the alteration seems to be dependent upon the amount of fracturing in the rock. For example, in the Toburn mine the syenite porphyry shows reddish alteration for a distance of about 600 feet north of the South vein. At the other end of the camp, irregular areas of alteration occur throughout the system of hanging-wall veins in the Macassa mine which attain a width of 325 feet. It would appear that the period of intense carbonatization preceded the period of ore deposition and that zones of carbonatization and gold-bearing veins do not necessarily coincide, although in most cases they have followed the same channelways. The same conclusions would apply to the Larder Lake fault zone lying to the south of the Kirkland Lake camp, where there is a much great development of carbonates. It implies widespread carbonatization throughout the country along lines of weakness as a forerunner of the gold mineralization.
>
> Silicification and sericitization are generally limited to areas immediately adjacent to the veins and may show a rather sharp contact with the country rock. The H vein in the Teck-Hughes mine and certain veins in the Sylvanite show varying degrees of silicification along the vein walls. Silicification is seen in breccia fragments of syenite or syenite porphyry within the quartz veins where very fine quartz partly replaces the fragments. Microscopic examination of the vein material along the K vein in the Teck-Hughes mine shows a very high degree of sericitization.
>
> The alteration of the different types of wall rock may show a slight difference in appearance, but in many places it only makes the identification of the original country rock more difficult. The syenite generally becomes a more pronounced red or pink; the dark-coloured augite syenite becomes more mottled in appearance, the ferromagnesian minerals being bleached and the feldspars reddened. In many places the syenite porphyry changes to a buff-coloured crush breccia or mixture of buff-coloured, reddish, and cherty phases. The sediments and tuffs do not show the same degree of alteration but tend to become red, brown, or green adjacent to innumerable tiny fractures. The various colours are due to disseminated dusty particles of red hematite, brown limonite, or goethite, and to varying quantities of ferriferous carbonate and sericite.

Thomson (1950) gives an extended list of analyses from which Table 49 was compiled. In general the alteration of the syenite porphyry, syenite and augite syenite has involved an increase in CaO, MgO, CO_2 and S. Some varieties of the altered syenitic rocks exhibit gains in SiO_2; others are characterized by significant losses.

Cordova deposit, Ontario (Precambrian: Grenville age). The Cordova Mine, near Marmora, Ontario was developed in a number of shear zones cutting a gabbro stock of variable composition and texture near a large mass of diorite. The age of the rocks is Grenville, and the age of the deposit is probably the same. In the vicinity of the old mine workings the gabbro is coarse grained and relatively equigranular. In the shear zones the minerals of the diorite are largely destroyed and replaced by chlorite and chlorite-carbonate schist. The width of these schist zones is relatively narrow, a few inches to 1 ft in most places. The veins and lenses are composed essentially of quartz with minor carbonate, small amounts of pyrite, ilmenite and native gold. The grade of the deposit is 0.3 oz Au/ton and 0.03 oz Ag/ton. The gold is mainly free.

In thin sections the plagioclase, hornblende and pyroxene of the gabbro are seen to be altered to a schistose mass of carbonate, quartz, biotite and/or chlorite, with some pyrite and minor ilmenite close to the quartz veins. As seen from the analyses in Table 50 there is a decrease in SiO_2 content as the alteration increases and the vein is approached. Concomitently an increase in CO_2, S and P_2O_5 is noted. K_2O is enriched in the chlorite-biotite-carbonate phase. H_2O shows a major increase in the biotite-chlorite phase and only a slight increase

Table 49. Chemical changes produced by alteration of syenite porphyry, Kirkland Lake area, Ontario

	Augite syenite	Syenite	Syenite porphyry	Wall rock and mylonite									Ore		
Constituent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
								(%)							
SiO_2	50.24	57.02	62.19	63.61	59.59	49.92	46.00	58.83	67.84	69.91	67.24	49.24	48.67	58.76	66.23
Al_2O_3	16.43	18.30	14.85	14.96	12.46	15.44	12.48	14.46	12.73	10.77	12.27	12.64	11.64	12.51	13.31
Fe_2O_3	2.77	0.98	1.38	1.08	0.94	0.97	3.00	1.37	1.37	1.51	0.12	0.41	1.49	0.91	(Fe)2.58
FeO	4.48	2.67	2.03	1.16	2.41	4.78	7.10	2.23	1.73	0.74	1.49	4.96	6.07	3.00	
MgO	3.80	1.04	2.33	1.85	2.80	3.79	6.45	3.69	1.71	0.75	1.80	3.14	5.88	3.04	1.68
CaO	5.84	1.99	3.88	3.36	5.51	5.82	6.90	4.77	3.13	4.58	3.90	10.36	6.69	4.76	3.64
Na_2O	3.54	4.25	4.92	4.30	3.82	4.49	2.85	5.44	5.34	4.00	4.60	4.82	1.86	2.78	7.06
K_2O	5.84	7.41	3.76	4.12	2.80	4.52	2.89	2.12	1.58	1.37	1.69	0.80	4.36	4.63	
H_2O (total)	1.90	0.95	1.05	0.91	0.88	1.40	2.32	0.71	0.74	0.89	0.68	0.77	1.84	1.31	
CO_2	3.35	3.06	2.79	4.08	7.68	7.22	8.20	5.96	3.10	3.64	5.06	11.84	8.86	5.91	3.10
TiO_2	0.93	1.90	0.44	0.42	0.39	0.98	0.81	0.45	0.28	0.25	0.28	0.65	0.86	0.55	
P_2O_5	0.51	0.23	0.37	0.26	0.35	0.42	0.55	0.06	0.10	none	0.12	0.15	0.13	0.22	
S								0.45	0.12	1.10	0.19	0.29			0.70
Cr_2O_3								none	0.08	none	trace	trace			
MnO	0.16	0.17	0.13	0.10	0.06	0.09	0.21	0.09	0.02	0.12	0.11	0.14	0.13	0.09	
FeS_2					0.28	0.30							1.81	1.59	
Total	99.79	99.97	100.12	100.21	99.97	100.14	99.76	100.63	99.87	99.63	99.55	100.21			
Specific gravity	2.819	2.681	2.730	2.699	2.689	2.750	2.805								

Source: Thomson (1950).

Notes:
1. Average of rock type based on 5 analyses of least altered material.
2. Average of rock type based on 2 analyses of least altered material.
3. Average of rock type based on 4 analyses of least altered material.
4. Altered porphyry from the north wall of the South vein, 1500-foot level, Wright-Hargreaves Mine.
5. Altered porphyry from the wall of an ore shoot on the main (north) vein, 600-foot level, Lake Shore Mine.
6. Altered syenite from the wall of a vein on the 2350-foot level, Kirkland Lake Gold Mine.
7. Altered augite syenite (lamprophyre) from the south wall of the main vein, 2475-foot level, Kirkland Lake Gold Mine.
8. Mylonite from No. 4002 drift, south vein, 4000-foot level, Wright-Hargreaves Mine.
9. Mylonite from No. 6102 drift, south vein, 6150-foot level, Wright-Hargreaves Mine.
10. Cherty phase of mylonite, No. 4801 west drift, 4825-foot level, Lake Shore Mine.
11. Buff-coloured mylonite, main south break, southeastern section, 1000-foot level, Sylvanite Mine.
12. Mylonite on No. 5 strike fault, shaft station, 5400-foot level, Sylvanite Mine.
13. Sample representing the mill run for 1 month from Kirkland Lake Gold Mine.
14. Sample representing 10 849 tons of ore milled at the Lake Shore Mine.
15. Analysis of representative mill feed, Wright-Hargreaves Mine.

in the highly altered phase near the veins. Al_2O_3, Fe_2O_3, FeO, CaO, MgO and MnO show a few changes, but these are not marked.

The trace and minor elements exhibit a varied habit. Those showing increases as the veins are approached include, Li, Rb, Cs, Cu, Ag, Au, Ba, B, Sn, Zr, As, Bi and V; those marked by decreases comprise Sr, Zn, Ga and Ni. Elements such as As, Sb and Bi show a definite correlation with the increase in pyrite as the veins are approached. Consistent increases in the K_2O/Na_2O and Au/Ag ratios and decreases in the SiO_2/CO_2 and SiO_2/total volatiles as the veins are approached are notable.

Bralorne Mine, Bridge River district, British Columbia, (Mesozoic age). The Bralorne deposit in the Bridge River district of British Columbia consists of gold-bearing quartz veins and silicified zones, mainly in a diorite stock of Mesozoic age. The diorite varies considerably in composition from an augite to a hornblende diorite. The veins are quartz-filled fissures that strike across the diorite. Adjacent to the veins the diorite is altered to chlorite and chlorite-carbonate-sericite schist over widths of several feet. The principal vein minerals are quartz, calcite, mariposite, arsenopyrite and pyrite, with minor amounts of scheelite, sphalerite, pyrrhotite, chalcopyrite, stibnite, galena and molybdenite. Native gold is the economic mineral. Joubin (1948) has described the deposit in some detail.

As shown by the analyses in Table 51, there is a decrease in SiO_2 as the alteration increases and the vein is approached. Attending this decrease there is a marked increase in CO_2, H_2O, S, K_2O and P_2O_5. Na_2O shows a general decrease as the ore is approached. Al_2O_3 remains nearly constant throughout the alteration sequence; there is a general decrease in Fe_2O_3 in the heavily chloritized zones and an increase in FeO, CaO, MnO, TiO_2 and MgO. The total iron content remains relatively constant, increasing slightly in the chlorite phases.

There is a general increase in the contents of the following trace elements as the veins are approached: Li, Rb, Cs, Ag, Au, Be, Ba, Hg, B, Sc, Pb, As, Sb, V, Cr, Mo, W, Cl, Co and Ni. The smooth increase is commonly broken in the highly altered carbonate-sericite schist, some elements such as Cu, Be, Sc, Cl and Ni being depleted in this zone compared with the original diorite. The element zinc shows a general decrease towards the vein, and cadmium, zirconium and fluorine exhibit an erratic behaviour. Strontium follows calcium closely, whereas barium follows potassium in the alteration sequence.

The data on the ratios show changes similar to those noted for the Yellowknife deposits. There is a marked increase in the K_2O/Na_2O ratios and a consistent decrease in the SiO_2/CO_2 and SiO_2/total volatiles as the gold-quartz veins are approached. The Au/Ag ratio shows a general increase towards the veins.

Table 50. Chemical changes produced by alteration of gabbro, Cordova Mine, Cordova, Ontario

Constituent	Gabbro*	Biotite-chlorite schist†	Adjusted§	Gains and losses in constituents	Percentage gains and losses	Gabbro*	Chlorite-biotite-carbonate schist‡	Adjusted§	Gains and losses in constituents	Percentage gains and losses
		(%)					(%)			
SiO_2	45.5	42.2	38.32	−7.18	−15.78	45.5	39.0	38.53	−6.97	−15.32
Al_2O_3	13.8	13.1	11.90	−1.90	−13.77	13.8	12.5	12.35	−1.45	−10.51
Fe_2O_3	3.0	1.55	1.41	−1.59	−53.00	3.0	4.55	4.50	+1.50	+50.00
FeO	10.6	10.8	9.81	−0.79	− 7.45	10.6	8.55	8.45	−2.15	−20.28
CaO	10.5	9.05	8.22	−2.28	−21.71	10.5	10.5	10.37	−0.13	−1.24
MgO	7.35	6.75	6.13	−1.22	−16.60	7.35	6.30	6.22	−1.13	−15.37
Na_2O	2.5	2.80	2.54	+0.04	+1.60	2.5	1.00	0.99	−1.51	−60.40
K_2O	0.35	0.30	0.27	−0.08	−22.86	0.35	1.00	0.99	+0.64	+182.86
H_2O (total)	2.00	4.20	3.81	+1.81	+90.50	2.00	2.10	2.08	+0.08	+4.00
TiO_2	2.67	1.69	1.54	−1.13	−42.32	2.67	2.03	2.01	−0.66	−24.72
P_2O_5	0.25	0.14	0.13	−0.12	−48.00	0.25	2.05	2.03	+1.78	+712.0
MnO	0.23	0.19	0.17	−0.06	−26.09	0.23	0.23	0.23	0.00	0.00
CO_2	0.20	7.1	6.45	+6.25	+3125	0.20	7.65	7.56	+7.36	+3680
S	0.14	0.22	0.20	+0.06	+42.86	0.14	1.57	1.55	+1.41	+1007.14
$O\equiv S$	0.06	0.09				0.06	0.59			
Total	99.1	100.0				99.1	98.6			
Specific gravity	3.114	2.826				3.114	3.076			
				(ppm)						
Li	8	10.5				8	12			
Rb	15	13.5				15	22			
Cs	0.3	<0.1				0.3	2.0			
Cu	39	36				39	82			
Ag	1.0	1.8				1.0	1.3			
Au	0.015	0.03				0.015	1.8			
Sr	230	220				230	190			
Ba	180	180				180	305			
Zn	91	85				91	84			
Cd	1	1				1	<1			
Hg (ppb)	54	58				54	52			
B	nf	nf				nf	490			
Ga	5.4	3.3				5.4	3.1			
Sc	54	27				54	53			
Y	32	<30				32	34			
Yb	<10	<10				<10	<10			
U	0.1	0.1				0.1	1.1			
Th	3	3				3	1			
Sn	<0.4	<0.4				<0.4	2.5			
Pb	5.0	2.9				5.0	5.1			
Zr	87	60				87	108			
As	12	8				12	29 600			
Sb	1	2.5				1	2.5			
Bi	<0.5	<0.5				<0.5	3.2			
V	500	315				500	885			
Se	<2	<2				<2	<2			
Te	<0.2	<0.2				<0.2	1.0			
Cr	44	45				44	<20			
Mo	1	2				1	2			
W	3	5				3	7			
F	600	550				600	620			
Cl	300	100				300	500			
Co	43	44				43	42			
Ni	47	22				47	22			
Pt (ppb)	<5	<5				<5	nf			
Pd (ppb)	<5	<5				<5	8			
Ratios										
K_2O/Na_2O	0.14	0.11				0.14	1.0			
SiO_2/CO_2	227.5	5.94				227.5	5.10			
$SiO_2/H_2O + CO_2 + S + As$	19.43	3.66				19.43	2.73			
Au/Ag	0.015	0.017				0.015	1.38			

Note: nf—not found.

*Composite sample of fresh gabbro.

†Composite sample of biotite-chlorite schist derived from gabbro (18–6 in. from vein).

‡Composite sample of chlorite-biotite-carbonate schist derived from gabbro (6–0 in. from vein).

§Adjusted % = percentages of biotite-chlorite schist† and chlorite-biotite-carbonate schist‡ multiplied by the specific gravity factors 0.908 and 0.988 respectively to reduce to a common volume.

Other deposits in intermediate and basic intrusive and extrusive rocks. Throughout the world numerous gold deposits in intermediate and basic intrusive and extrusive rocks exhibit wall-rock alteration features similar to those just described. A brief review of some significant examples follows.

Lindgren (1905–1906, p. 539), after a study of some gold ores from Western Australia where the lodes occur mainly in amphibolites (greenstones), concluded that the alteration processes were as follows:

> The metasomatic processes consist then in the introduction of carbon dioxide and sulphur with gold, mercury and tellurium and the attendant development of carbonates at the expense of the lime, magnesia, and iron contained in the chlorite and amphibole, and of pyrite at the expense of the same minerals and the black iron ores. The silica set free by the decomposition of the silicate has been deposited as quartz where it was not needed for the formation of the new silicates sericite and albite.

Ransome (1909) describes the characteristic alteration of Tertiary dacites, latites, rhyolites and andesites associated with the gold-silver lodes of Goldfield, Nevada. The dacites, containing some 60 per cent SiO_2 and 2.5 and 3 per cent respectively of K_2O and Na_2O, are highly altered in the vicinity of the lodes to a comparatively soft rock containing essentially quartz, kaolinite, alunite and pyrite. During the alteration the dacite has been depleted in some of its silica, much of its Al_2O_3, MgO and CaO and some of its Na_2O and K_2O. Gains are represented by H_2O, S and SO_4. The iron present in the original rock was more than sufficient to form all of the pyrite. The alunitization process is extensive within the dacite and other rocks, expanding over widths of a mile in places and extending over a considerable area (*see* Fig. 32). The known productive gold areas are within the alunite halo but are relatively small compared with the area covered by the halo.

In a more recent investigation of the wall-rock alteration associated with the gold deposits of the Goldfield district, Harvey and Vitaliano (1964) distinguished the following mineralogical zones, which flank the veins in the Tertiary dacites, latites and andesites:

1. A propylitic zone farthest from the veins and characterized by the development of chlorite, chlorite-vermiculite, calcite and antigorite.
2. A bleached argillic zone, divided into a montmorillonite subzone in the outermost part and an illite-kaolinite subzone in the innermost part.
3. An alunite-quartz zone immediately adjacent to the veins in which alunite, quartz, hematite, jarosite, halloysite, gypsum, epidote and sulphides are present. The investigators postulate that alunite was formed by the reaction of sulphuric acid and K-mica. Thermodynamic data are given for the reaction.

Clapp (1915) describes alunitized and pyrophyllitized dacites and andesites of Triassic and Jurassic age from Kyuquot Sound, Vancouver Island. These rocks, now mainly quartz-sericite-chlorite, quartz-sericite, quartz-pyrophyllite and quartz-alunite (natroalunite) rocks, are pyritized in places and contain small amounts of gold (0.05 oz/ton) and silver (0.5 oz/ton). The analyses given by Clapp indicate that alunitization and sericitization of the rocks lead to an increase in S, SO_4 and H_2O. Decreases were noted for iron oxides, MgO and CaO, as well as Na_2O. SiO_2, Al_2O_3 and K_2O have

Table 51. Chemical changes produced by alteration of diorite, Bralorne Mine, Bridge River district, British Columbia

Constituent	Fresh diorite*	Chloritized diorite†	Adjusted''	Gains and losses	Percentage gains and losses	Fresh diorite*	Chlorite-sericite schist‡	Adjusted''	Gains and losses	Percentage gains and losses	Fresh diorite*	Carbonate-sericite schist§	Adjusted''	Gains and losses	Percentage gains and losses
		(%)					(%)					(%)			
SiO_2	56.9	43.6	44.91	−11.99	−21.07	56.9	41.4	41.23	−15.67	−27.54	56.9	42.9	43.54	−13.36	−23.48
Al_2O_3	15.6	16.3	16.79	+1.19	+7.63	15.6	16.8	16.73	+1.13	+7.24	15.6	18.1	18.37	+2.77	+17.76
Fe_2O_3	1.8	1.1	1.13	−0.67	−37.22	1.8	0.9	0.896	−0.904	−50.22	1.8	1.8	1.83	+0.03	+1.67
FeO	5.9	8.7	8.96	+3.06	+51.86	5.9	7.8	7.77	+1.87	+31.69	5.9	5.5	5.58	−0.32	−5.42
CaO	6.2	9.7	9.99	+3.79	+61.13	6.2	8.7	8.67	+2.47	+39.84	6.2	6.4	6.50	+0.30	+4.84
MgO	4.9	7.2	7.42	+2.52	+51.43	4.9	5.7	5.68	+0.78	+15.92	4.9	2.4	2.44	−2.46	−50.20
Na_2O	4.0	2.7	2.78	−1.22	−30.50	4.0	1.6	1.59	−2.41	−60.25	4.0	2.3	2.34	−1.66	−41.50
K_2O	0.3	0.6	0.62	+0.32	+106.67	0.3	2.6	2.59	+2.29	+763.3	0.3	3.6	3.65	+3.35	+1116.7
H_2O (total)	2.7	4.6	4.74	+2.04	+75.56	2.7	5.1	5.08	+2.38	+88.15	2.7	4.4	4.47	+1.77	+65.56
TiO_2	0.47	0.72	0.74	+0.27	+57.45	0.47	0.59	0.588	+0.118	+25.11	0.47	0.78	0.79	+0.32	+68.09
P_2O_5	0.03	0.02	0.021	−0.009	−30.00	0.03	0.23	0.229	+0.199	+663.3	0.03	0.13	0.132	+0.102	+340.0
MnO	0.14	0.15	0.16	+0.02	+14.29	0.14	0.13	0.129	−0.011	−7.86	0.14	0.18	0.183	+0.043	+30.71
CO_2	0.2	2.8	2.88	+2.68	+1340.	0.2	6.7	6.67	+6.47	+3235.	0.2	9.1	9.24	+9.04	+4520.
C	0.1	0.1				0.1	nf				0.1	nf			
S	0.16	0.18	0.185	+0.025	+15.63	0.16	0.46	0.458	+0.298	+186.3	0.16	1.44	1.46	+1.30	+812.5
O≡S, Cl, F	0.07	0.07				0.07	0.19				0.07	0.54			
Total	99.3	98.3				99.3	98.6				99.3	98.5			
Specific gravity	2.823	2.909				2.823	2.812				2.823	2.865			

			(ppm)			
Li	16	38	16	52	16	47
Rb	5	15	5	46	5	64
Cs	0.6	3.5	0.6	3.5	0.6	4.2
Cu	50	39	50	83	50	25
Ag	1.3	1.5	1.3	1.6	1.3	1.8
Au	0.015	0.01	0.015	0.4	0.015	0.8
Be	2	4	2	5	2	<2
Sr	220	360	220	140	220	190
Ba	86	270	86	160	86	570
Zn	68	59	68	54	68	47
Cd	1.3	2.5	1.3	1.3	1.3	2.5
Hg (ppb)	17	8	17	46	17	285
B	53	69	53	150	53	150
Sc	46	56	46	60	46	33
U	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Pb	10	15	10	20	10	15
Zr	60	nf	60	nf	60	52
As	13	19	13	63	13	17 000
Sb	<1	<1	<1	2	<1	16
Bi	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
V	240	390	240	440	240	300
Se	<2	<2	<2	<2	<2	<2
Te	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Cr	46	140	46	180	46	75
Mo	1	1	1	2	1	4
W	<2	<2	<2	8	<2	28
F	200	<200	200	200	200	<200
Cl	<200	<200	<200	400	<200	<200
Co	42	59	42	78	42	57
Ni	41	62	41	83	41	34
Pt (ppb)	nf	<5	nf	nf	nf	nf
Pd (ppb)	<5	<5	<5	<5	<5	nf
Ratios						
K_2O/Na_2O	0.08	0.22	0.08	1.63	0.08	1.57
SiO_2/CO_2	284.5	15.6	284.5	6.2	284.5	4.7
SiO_2/H_2O+CO_2+ S+As	18.6	5.8	18.6	3.4	18.6	2.6
Au/Ag	0.012	0.007	0.012	0.25	0.012	0.44

Note: nf–not found.

*Composite sample of fresh diorite (country rock) (25–50 ft from vein).

†Composite sample of chloritized diorite (chlorite schist) (10–25 ft from vein).

‡Composite sample of chlorite-sericite schist (1–5 ft from vein).

§Composite sample of carbonate-sericite schist (0–1 ft from vein).

‖Adjusted % = percentages of chloritized diorite†, chlorite-sericite schist‡ and carbonate-sericite schist§ multiplied respectively by the specific gravity factors 1.030, 0.996 and 1.015 to reduce to a common volume.

increased in some rocks and decreased or remained constant in others.

Simpson and Gibson (1912) give a series of analyses of typical Kalgoorlie rocks in which the propylites (chlorite-carbonate schist) and carbonated parts show substantial losses of silica and gains of carbon dioxide, sulphur and potash when compared with the amphibolites, gabbros and epidiorites from which they were derived. The analyses given by Feldtmann (1916) for the East Coolgardie goldfield exhibit similar features. A suite of analyses of specimens from Ora Banda (40 mi northwest of Kalgoorlie) given by Clarke and Ellis (1939), however, show an increase in the silica content as the veins are approached. The specimens were, however, not in a complete sequence from one crosscut.

In a more recent contribution to the subject of wall-rock alteration associated with the auriferous lodes of Kalgoorlie, Bartram and McCall (1971) note extensive regional carbonatization of the greenstones (dolerite) with the development of chlorite, albite, quartz, carbonates and minor muscovite. Weak carbonatization resulted in the formation of calcite whereas intense carbonatization produced both ankerite and calcite. All of the gold lodes occur within these altered zones and are flanked by zones enriched in sericite. No relationship was found between the gold values and the type of intensity of wall-rock alteration. Considering the overall chemical features at Kalgoorlie there is a general similarity to the alteration processes at Yellowknife. In both auriferous belts CO_2, H_2O, S and K have been introduced, and there has been a marked leaching of SiO_2. The exchange reaction between K and Na resulting in significant loss of Na does not appear to have been as pronounced at Kalgoorlie as at Yellowknife. In both belts there is little or no change in the total iron content from country rock to pyritic lode, indicating that most of the iron component was contributed by the host rocks and bound by the introduced sulphur.

Bartram and McCall (1971) seem to think that the regional carbonatization and lode formation are distinct processes, despite the fact that the lodes are always found in the zones of carbonatization. They say "Several lines of evidence suggest that the carbonatising solutions invaded the greenstone after regional metamorphism, that these solutions were active over a long period, and that their activity commenced before the major lode formation was completed." Commenting on the progressive changes in the nature of the solutions they state: "Either the hydrothermal solutions changed progressively, with time, becoming richer in potassium and poorer in carbon dioxide, or else there were two distinct phases of alteration, comprising an earlier carbon dioxide-rich phase and a later potassium-rich phase."

This view has been prevalent in the literature for many years. The writer can find no satisfactory evidence to substantiate changing solutions or pulsation effects in the alteration zones of epigenetic gold deposits. On the contrary it seems more logical from the field evidence and the chemistry involved that the formation of quartz lodes was concomitant with carbonatization. This statement is amplified further in the section on the origin of gold deposits at the end of this chapter.

McCann (1922), in his study of gold-quartz veins at the Bridge River district, British Columbia, where the veins occur in augite diorite, found a strong desilication of the adjacent wall rocks and concomitant increases in CO_2, H_2O, S, As and K_2O. He made comparisons with the Grass Valley and Juneau, Alaska gold deposits and found similar phenomena. About the silica he says (p. 364), "the silica which has been lost has probably contributed to vein filling . . ." Na_2O was leached from the highly altered carbonate sericite schist, as were also the oxides of iron, aluminum and magnesium. These results are essentially the same as those noted in the Bralorne Mine as described above.

Knopf (1929, p. 47) in his description of the Mother Lode System in California observed, after considering the alteration adjacent to the veins in greenstones, amphibolites and serpentinites that, "the carbon dioxide liberated immense quantities of silica from the wall rocks, and this silica was delivered to the vein channels, where it was in part precipitated as quartz."

At Porcupine, Ontario, Hurst (1935) found that during the alteration processes of the dacite, pillow lava (greenstone) and quartz porphyry in which the orebodies occur, the content of silica was decreased substantially in the altered equivalents of these rocks adjacent to the quartz bodies. K_2O and S showed marked gains, and CO_2 increased in the altered dacite. Na_2O exhibited an increase in the altered dacite and decreases in the altered pillow lava and porphyry.

Bateman (1940), in his description of the character of the wall-rock alteration in the Uchi Lake greenstones in Ontario, gives analyses and remarks on the desilication of the alteration zones adjacent to the gold veins and orebodies. His analyses show a marked increase in the K_2O, S and CO_2 contents of the altered greenstones and a slight increase in the Na_2O content.

In the Nighthawk Peninsular Gold Mine in the Porcupine Camp of Ontario the orebodies are carbonate zones with quartz stringers and disseminated sulphides in or near a stock of albite syenite intruding Keewatin lavas (andesites). Byers (1940) found that during the alteration of the syenite to a carbonate-sericite and carbonate-chlorite rock there was a decrease in SiO_2, Na_2O, Al_2O_3 and an increase in MgO, CaO, K_2O, FeO and H_2O.

Davidson and Banfield (1944), describing the alteration associated with the Beattie gold deposits that occur in syenite porphyry, give analyses showing a desilication of the syenite porphyry as the vein is approached. There is also a concomitant increase in K_2O, CO_2 and S, and a decrease in Na_2O. The andesite greenstone, however, shows an increase in silica as the orebody is approached. Only two analyses are given and it is difficult to draw conclusions. The andesite (dark greenstone) does not appear to be a normal sample of greenstone country rock, since it contains 29.70 per cent SiO_2 and 18.75 per cent $CaCO_3$. It probably represents a phase of the alteration zones.

Tooker (1963) made an extensive study of the primary wall-rock alteration of the auriferous base metal veins in the central part of the Front Range mineral belt, Gilpin and Clear Creek counties, Colorado. The host rocks are varied and include Proterozoic granite, granodiorite, granite gneiss, quartz diorite, amphibolite, garnet-gneiss and biotite schist, and Tertiary quartz monzonite and bostonite porphyry dykes and plutons (Fig. 48). The alteration zones flanking the veins range from a few tens of centimetres to several metres and consist essentially of an inner zone marked by extensive sericitization that grades outward through successive zones of strongly argillized rock and weakly argillized rock to fresh rock. The alteration zones are said to have been developed largely prior to the gold-base metal mineralization. Extensive mineralogical and geochemical data are given to which the interested reader should refer for details. Briefly, Tooker considered the distribution of elements in the altered wall rocks to be largely the result of the movement of ions in and out of the interstices of a silicon-oxygen or aluminum-oxygen framework in which the oxygen ion positions are the most abundant and largest. Calculations from chemical analyses of samples of representative rocks showed that, in the alteration of equal volumes of rock, small amounts of K^+, Fe^{2+}, C^{4+}, H^+, S^{2-}, and at places Al^{3+} were added, and Si^{4+}, Na^+, Ca^{2+}, Fe^{3+} and Mg^{2+} were removed. In a chemical sense, this is interpreted as a hydrolysis process in which there is a replacement of chemical equivalents of metal cations by H^+ ions, which enter the structure and produce polarized hydroxyl groups. The hydrothermal solutions that altered the rocks, as inferred by Tooker from observable surface and underground waters and the mineralogical and chemical changes in the host wall rocks, were relatively dilute, slightly acid and initially carried K and subsequently CO_2 and S ions or complexes. As the rocks were altered, these solutions were modified by constituents replaced in the wall rocks and by vein-forming ore metals.

In the Tertiary (Neogene) deposits in the Rodalquilar area of southeast Spain Lodder (1966) recognized the following zones from the ignimbrite wall rocks inward toward the veins: (1) least altered ignimbrite characterized by mixed-layer chlorite-vermiculite, illite, chlorite and carbonate; (2) a zone characterized by mixed-layer smectite-chlorite, illite, smectite, chlorite, carbonate, sulphides, iron oxides and minor gypsum; (3) a zone marked by mixed-layer illite-smectite, illite, smectite, quartz, adularia, plagioclase, sulphides, alunite, jarosite and minor gypsum, iron oxides and strongly leached biotite; (4) a kaolinite-illite zone marked by kaolinite, illite, quartz, adularia, plagioclase, jarosite, alunite and minor gypsum, sulphides and iron oxides; (5) a zone in which dickite is abundantly developed together with quartz, alunite, jarosite, illite, locally pyrophyllite, sulphides and iron oxides; and (6) alunite-quartz which comprises the veins. The principal mineral constituents are fine-grained banded vein quartz, alunite, jarosite, barite, gypsum, zircon, apatite, rutile, iron oxides, sulphides and gold. The widths of the zones are variable; the outer zones may range from 70 to 150 m in width whereas the inner dickite zone is rarely more than 0.5 m except where pyrophyllite is present in which case this zone may range up to 5 m wide. The alunite-quartz (vein) zone varies in width from 1 cm to 1.7 m.

The chemical analyses presented by Lodder (1966) show significant decreases in silica content in some of the outer zones with a gradual increase toward the alunite-quartz zone. Alumina contents show a reverse relationship to those for silica. There is a gradual decrease in the potassium and sodium contents of the rocks as the veins are approached. The K_2O/Na_2O ratios across the alteration zones show an unusual erratic behaviour, probably because the samples are not from the same traverse across the veins.

Taneda and Mukaiyama (1970) discussed the wall-rock alteration processes at the Kushikino Mine, southern Kyushu, Japan. The host rocks are Tertiary pyroxene andesites, which are propylitized; in the hanging walls of the veins sericitization is marked, and in the footwalls silicification is predominant, the silicified rocks consisting mainly of quartz, sericite, adularia, calcite and pyrite. Analyses of the altered footwall rocks show marked increases in the content of silica and decreases in Ti, Al, Fe, Mn, Ca, Mg, Na and K.

Weissberg and Wodzicki (1970) investigated the wall-rock alteration at the Tui Mine, Te Aroha, New Zealand. The deposit in this mine is a fault-controlled, open-space filling type, containing essentially lead-zinc-copper sulphides, and is typical of the epithermal gold-silver and base metal ore deposits that occur as lodes in fissures and faults in extensively altered Tertiary andesite lavas and pyroclastic rocks.

They observed that the hydrothermal alteration is zonally arranged around the lodes, increasing in intensity towards them. It is characterized by the following sequential mineralogical changes: (1) pyroxene to chlorite (plus carbonate and epidote), magnetite to pyrite; (2) plagioclase to K-feldspar (plus carbonate and epidote); (3) K-feldspar to sericite; and (4) intense silicification and obliteration of original textures. Interlayered montmorillonite-illite and minor kaolinite occur throughout most of the altered sequence and are probably of retrograde origin. These mineralogical changes are accompanied by a small gain of sulphur, carbon dioxide, water, potassium, manganese and possibly silica, and a loss of calcium and possibly minor magnesia and alumina.

The textural evidence indicated that at a given location K-feldspar preceded sericite, and kaolinite was the last mineral to crystallize, suggesting that the temperature and/or the ratio K^+/H^+ decreased with time. Similar hydrothermal minerals occur in the active hydrothermal fields of the Taupo volcanic zone, where their different spatial distribution probably reflects present day variations in physical and chemical conditions rather than changes in these conditions through time.

They further noted that the intensity of hydrothermal alteration and the concentration of As, Sb, Cu, Pb, Zn and Hg in the wall rocks increased with proximity to the lodes and other permeable zones. From this they concluded that the zoned alteration pattern is genetically related to ore emplacement and that the ore metals were added to the lodes and wall rocks by hydrothermal transport along fissures.

Farther north in the Coromandel Peninsula of New Zealand the host rocks of the Hauraki auriferous deposits are extensively propylitized over great widths, some zones exceeding 1000 ft or more. These zones occur mainly in the First Period volcanics, which consist mainly of Eocene andesitic breccias and flows with minor amounts of associated dacitic and rhyolitic rocks. Finlayson (1909) studied the alteration in the andesites in great detail and gives analyses of fresh and highly altered (propylitized) hornblende andesite. Petrographically the fresh andesite passes through a chloritized phase into the propylitic phase (actually a zone consisting essentially of quartz, sericite, carbonate and pyrite) as the auriferous quartz veins are approached. The analyses of the fresh and highly propylitized andesite indicate that during chloritization and carbonatization processes silica is lost in the chloritized parts of the alteration zones and increased slightly in the rocks nearest the quartz veins. Carbon dioxide is gained in all altered rocks, and there is considerable loss of soda and a gain of potash and sulphur in the intensely altered sericite-adularia-pyrite phases next to the veins. Iron shows little change being bound mainly by sulphur into pyrite. Constituents like alumina, titania and phosphorus are reduced in the rocks adjacent to the veins; magnesia is also reduced with a corresponding increase in lime.

Bragg (1943) described the wall-rock alteration at the San Antonio Mine in southeastern Manitoba. The orebodies are veins and pyritized zones in a diabase sill. The alteration types recognized were epidotization, chloritization, carbonatization, albitization, silicification and sericitization. Orebodies were mainly characterized by carbonatization, pyritization, albitization and sericitization. More recently Stephenson (1971) has given an extensive series of analyses of wall rocks adjacent to the various types of gold deposits in the Rice Lake–Beresford Lake greenstone belt, southeastern Manitoba, which includes the San Antonio deposit. He noted depletions of SiO_2, Al_2O_3, CaO, MgO and Na_2O in the altered greenstones (quartz diorite, gabbro) and enrichments of K_2O, CO_2, H_2O, S and B. The total iron content changed only slightly. He concluded that silica removed from the alteration zones contributed to the quartz vein filling. Similar features were noted by Bailes (1971) for dacitic and diabasic rocks in the Pilot-Smuggler shear zone in the Rice Lake region. Amukun and Turnock (1971), however, concluded that there is no evidence that the material in the quartz veins of the Bissett area of Manitoba originated from the country rock.

In Taiwan there are a number of auriferous deposits in Tertiary rocks of which the Chinkuashih gold-copper lodes in dacites and Neogene sediments are the most important. Wang (1973) describes the wall-rock alteration attending these lodes in some detail. Outward from the great Penshan quartz sulphide vein in dacite there is a marked zonal arrangement consisting of a well developed silicified zone that grades through an argillized zone into a wide propylitized zone and then into unaltered dacite. In places the propylitized zone is several hundred metres wide. The other zones are much narrower, although the silicified zone approaches 100 m in near-surface parts of the vein.

The alteration processes associated with mineralization in Tertiary volcanic areas can be complex as shown by the work of Stanciu (1973) in the Gutîi Mountains, Romania. There, the volcanism occurred in three stages – the first, a rhyodacite (Tortonian-Buglovian) stage lacks hydrothermal activity; the second, an andesitic stage (Volhynian-Pontian) is marked by intensive hydrothermal effects and mineralization; and the third, a late andesitic stage (Upper Pliocene) has been slightly affected by hydrothermal alteration. Three hydrothermal phases mark the second volcanic stage, which is also the main metallogenic stage; the first is associated with the eruption of Sarmatian pyroxene andesites, the second is associated with the eruptions of Pannonian quartz andesites, and the third is associated with eruptions of Pontian pyroxene andesites. The first and second phases are characterized by alteration processes in succession as follows: propylitization, chloritization, development of adularia, sericitization, argillization and carbonatization. Adjacent to the veins the development of adularia is most persistent with sericitization and argillization notable in places. The propylitization and chloritization are commonly regional in aspect. During the third phase adularization was strongly diminished, but propylitization, sericitization and argillization were strongly manifest. Stanciu (1973) states that the cupiferous ore deposits are marked by chloritic zones; polymetallic veins mainly by adularization and subordinately by propylite zones; and gold-silver veins by widely developed adularia zones.

In a further contribution to wall-rock alteration effects in Tertiary andesites at the auriferous Hanes deposit in Romania Borcos and Stanciu (1974) note that the propylitization and sericitization of the andesites took place under pressure and at temperatures greater than 365°C in the presence of acidic hypervolatile emanations. They noted a marked replacement of sodium by potassium during alteration processes and concluded that when the K_2O content is greater than 3 per cent it can serve as an indicator of economic gold-silver mineralization.

Little has been said about the wall-rock alteration effects associated with certain gold-quartz deposits formed in the intermediate and basic rocks under deep seated conditions in high grade metamorphic terranes. The reason for this is that there are relatively few of these deposits, and only a small number have been studied intensively from the viewpoint of wall-rock alteration phenomena.

Briefly most of the wall-rock alteration effects in these deposits are minimal, the quartz bodies either grading into or being frozen against amphibolite or pyroxene schists and gneisses and other high grade intermediate-basic rocks. Commonly a zone of biotitization, chloritization and feldspathization occurs adjacent to the quartz bodies as at the Cordova Mine described above.

Summary of wall-rock alteration effects adjacent to gold deposits in intermediate and basic intrusive and extrusive rocks. The principal types of wall-rock alteration attending gold deposits in intermediate and basic intrusive and extrusive rocks are chloritization, carbonatization and sericitization. Silicification, present in some types of deposits, is relatively uncommon. Alunitization is restricted mainly to Tertiary deposits. Where chloritization, carbonatization and sericitization is marked there is generally a significant loss of SiO_2 and marked gains of CO_2, K_2O and S. Na_2O is commonly leached. Fe, Mn, Ca, Mg and Ti often show little change in most deposits, but in some there are significant additions or subtractions. H_2O is increased in the chloritized zones and generally decreased in the carbonate-sericite zones compared with the original rocks. Silicification is usually marked by a large increase in SiO_2 and decreases in elements such as Al, Fe, Mn, Ca, Mg, Ti, Na and K. Alunitization is commonly accompanied by a loss of silica in the wall rocks adjacent to the veins, and there is frequently also a loss of Na in some of the highly altered phases of the alteration zones. Marked increases in S always accompany this type of alteration. The behaviour of the other elements is variable.

Where carbonatization is marked in the alteration zones of epigenetic gold deposits in intermediate and basic rocks the ratio K_2O/Na_2O generally shows a consistent increase as the veins are approached. Similarly, there is usually a marked decrease in the SiO_2/CO_2 and SiO_2/total volatiles ratios with proximity to the veins. Where silicification and alunitization prevail the behaviour of these ratios tends to be variable.

Gold-quartz veins and silicified zones dominantly in acidic (granitic) intrusive and extrusive rocks. Deposits of this type commonly occur in volcanic terranes, the principal host rocks being rhyolites and effusive quartz-feldspar porphyries, now largely quartz-mica schists. Similar types of deposits also occur in granitic stocks and plugs and in intrusive quartz-feldspar bodies in various terranes.

Deposits of this type range in age from Precambrian to Tertiary. Characteristic examples of the Precambrian type in Canada include certain veins in the Yellowknife area; the Box Mine in northern Saskatchewan; a few veins in the Red Lake area of Ontario; the Renabi Mine in Ontario; and numerous veins and silicified zones in the Timmins area, Ontario. Elsewhere in the Precambrian, members of this type occur in the Kalgoorlie and Coolgardie districts of Western Australia, and in the Barberton district of South Africa.

Paleozoic and Mesozoic deposits of this type are widespread in Europe, Asia and the Western Cordillera of North America. A number of deposits of this type occur in the Ural goldfields; other examples include some of the veins of Grass Valley and Nevada City in California, and a number of deposits in British Columbia, including the Premier Mine at the head of Portland Canal, and others near Nelson.

Tertiary deposits of this type are, likewise, fairly widespread throughout the world, occurring in the gold districts of Romania, Japan, New Zealand, U.S.S.R. and United States (De Lamar, Idaho; Rawhide, Nevada; and Cripple Creek, Colorado). In all of these districts the acidic host rocks are mainly rhyolites and rhyodacites that accompany andesites and basalts. At Cripple Creek some of the host rocks in the mineralized volcanic neck are latites and phonolites; the country rocks are granite.

Yellowknife district, Northwest Territories (Precambrian: Archean age). Some of the veins and silicified zones in the Yellowknife Greenstone Belt cut quartz-feldspar porphyries that form dykes and regular bodies in the meta-andesites. The alteration of the porphyries adjacent to the veins is mainly sericitization and hydration.

The fresh quartz-feldspar porphyry contains essentially quartz, plagioclase, chloritized biotite and muscovite. Accessory minerals are pyrite, pyrrhotite, leucoxene, epidote and carbonate. Thin sections show that alteration of the rock results in the development of sericite from the plagioclase and biotite and a general recrystallization of the quartz and sulphides. In places an increase in sulphides is apparent.

The chemical analyses of the fresh and altered porphyry are given in Table 52 and graphed in Figure 14. They indicate relatively little change in the SiO_2, Fe_2O_3, TiO_2, P_2O_5 and MnO during the alteration process. Much calcium and carbon dioxide have migrated out of the sericite zone together with sodium and some iron. Potassium, alumina, water and sulphur were added.

The alteration processes, therefore, were mainly an exchange of potassium for sodium during hydration, and to balance the equilibrium, alumina was added and calcium abstracted. This calcium together with carbon dioxide probably formed carbonates in the quartz lenses. Some of the iron was fixed by sulphur in the alteration zones, and the remainder migrated to the site of the quartz lenses where it was probably fixed as pyrite.

Table 52. Chemical changes produced by alteration of quartz-feldspar porphyry, Negus-Rycon System, Yellowknife, Northwest Territories

Constituent	A-23*	A-24†	Adjusted‡	Gains and losses in constituents	Percentage gains and losses
		(%)			
SiO_2	73.09	72.46	73.80	+0.71	+ 1.06
Al_2O_3	14.01	16.26	16.56	+2.55	+18.30
Fe_2O_3	0.32	0.34	0.35	+0.03	+9.36
FeO	0.89	0.45	0.46	–0.43	–48.50
CaO	2.05	0.94	0.96	–1.09	–53.20
MgO	0.37	0.77	0.78	+0.41	+111.00
Na_2O	4.15	0.63	0.64	–3.51	–84.50
K_2O	1.63	3.94	4.01	+2.38	+146.00
H_2O+	0.72	1.93	1.97	+1.25	+174.00
H_2O-	0.05	0.12	0.12	+0.07	+140.00
TiO_2	0.20	0.25	0.26	+0.06	+30.00
P_2O_5	0.05	0.10	0.10	+0.05	+100.00
MnO	0.02	0.01	0.01	–0.01	–50.00
CO_2	1.80	0.97	0.99	–0.81	–45.00
S	0.80	1.27	1.29	+0.49	+61.20
Cl	trace	0.01	0.01	–	–
Cr_2O_3	0.04	trace	–	–	–
Total	100.19	100.45	–	–	–
Less O≡S,Cl	0.34	0.55	–	–	–
Net total	99.85	99.90	–	–	–
Specific gravity	2.69	2.74	–	–	–
	(ppm)				
Li	5	6			
Rb	58	171			
Cs	2.0	6.7			
B	28	34			
As	142	140			
Sb	6.2	22			
Ratios					
K_2O/Na_2O	0.39	6.25			
SiO_2/CO_2	40.61	74.70			
SiO_2/H_2O+CO_2+S	22.02	17.38			

* A-23—composite sample of massive quartz-feldspar porphyry, Con Mine.

† A-24—Composite sample of altered quartz-feldspar porphyry adjacent to quartz veins, Negus-Rycon System.

‡ Adjusted % = percentages in A-24 multiplied by the factor 2.74/2.69 to reduce a common volume.

Considering some of the trace elements it is apparent that there is an increase in the Rb, Cs, B and Sb content as the veins are approached. Li and As remain relatively constant.

There is a marked increase in the K_2O/Na_2O ratio as the gold-quartz veins are approached. The SiO_2/CO_2 ratio shows an increase that reflects the silicification of the alteration zone. There is a small decrease in the SiO_2/total volatiles ratio.

Red Lake area, Ontario (Precambrian: Archean age). The Red Lake Gold Shore Mine and the Howey and Hasaga mines occurred in granitic rocks in the Red Lake district of Ontario, the first in a granitic stock and the last two in a quartz porphyry dyke in greenstones. At the Howey and Hasaga mines the normal grey porphyry is altered to a buff waxy rock rich in sericite. The analyses (Table 53) given by Horwood

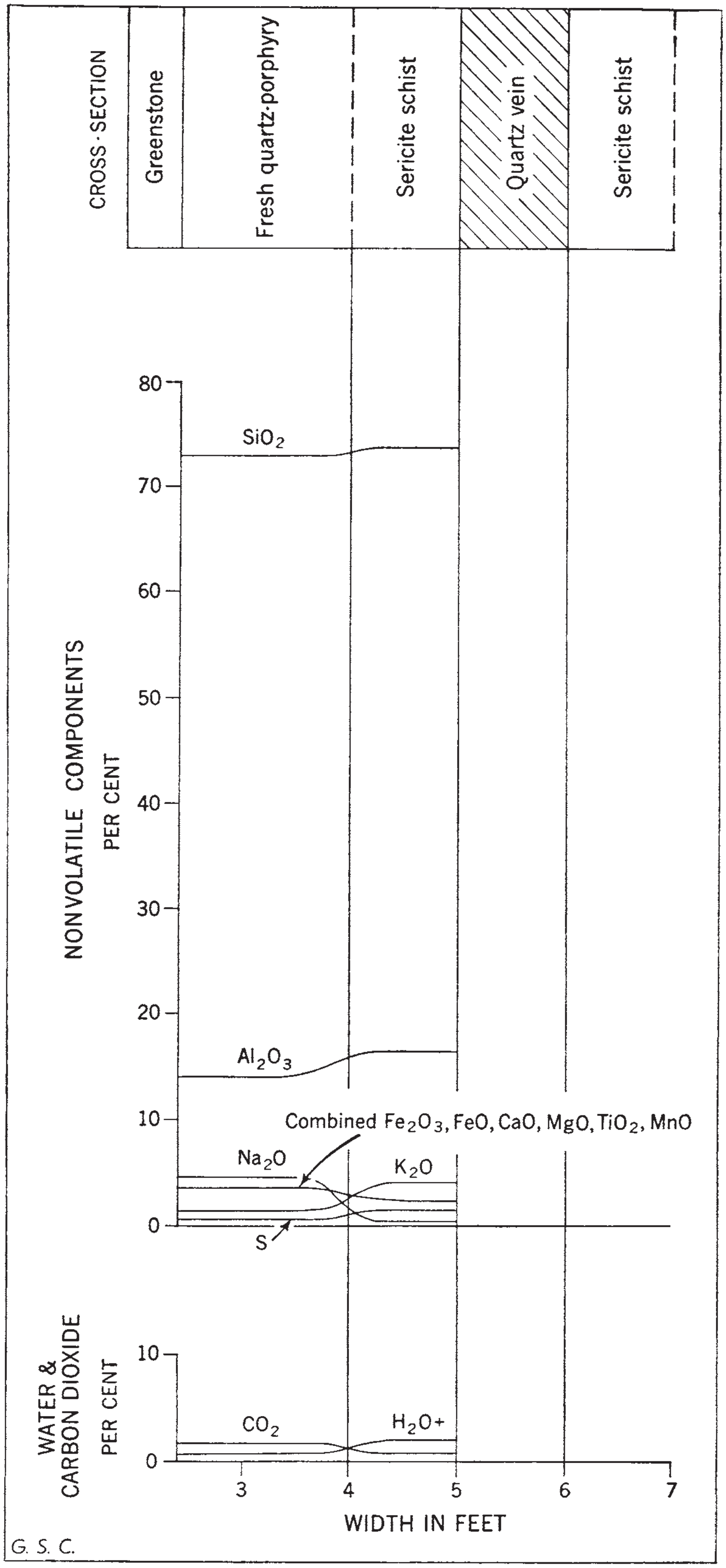

Figure 14. Chemical changes produced by alteration of quartz-feldspar porphyry, Negus-Rycon System, Yellowknife, Northwest Territories (*see* Table 52).

(1945) show a slight decrease in silica in the altered porphyry as the veins are approached, an increase in Al_2O_3, TiO_2, K_2O, CO_2 and H_2O and a decrease in Na_2O. The iron species exhibit an erratic behaviour; sulphur exhibits an increase in the slightly sericitized porphyry.

Table 53. Chemical changes produced by alteration of quartz porphyry, Howey Mine, Red Lake, Ontario

Constituent	Normal grey quartz porphyry	Partly sericitized porphyry	Highly sericitized porphyry
		(%)	
SiO_2	72.39	71.82	70.06
Al_2O_3	13.87	16.00	16.61
Fe_2O_3	1.45	0.10	1.80
FeO	1.13	0.36	0.85
MgO	0.46	0.21	0.51
CaO	1.24	1.07	1.10
Na_2O	4.75	4.62	3.32
K_2O	2.79	2.14	3.22
TiO_2	0.64	0.66	0.77
H_2O	0.43	1.27	1.34
CO_2	0.52	0.36	0.67
FeS_2	0.48	2.06	trace
Total	100.15	100.67	100.25

Source: Horwood (1945).

At the Red Lake Gold Shore Mine the host rocks of some of the quartz veins are granites and granodiorites with inclusions of greenstones. Near the veins the granitic rocks are silicified, sericitized, chloritized and moderately carbonated and pyritized.

The analyses given in Table 54 show a slight increase in SiO_2 and moderate to marked decreases in Al_2O_3, Fe_2O_3, FeO, CaO, MgO, TiO_2, P_2O_5 and MnO in the carbonate-sericite schist compared with the granite. Na_2O exhibits a small decrease in the sericite-carbonate schist, and K_2O remains relatively constant although some samples from this zone show a moderate increase of a percent or so. The major additions during sericitization and carbonatization are H_2O, CO_2 and S.

Lithium exhibits a decrease in the alteration zone, as does also cesium. Rubidium remains relatively constant. Increases as the veins are approached are apparent for the following trace elements: Cu, Au, B, Zr, As and F; decreases are registered by Sr, Ba, Zn, Cl and Co.

The K_2O/Na_2O ratio exhibits a slight increase as the gold-quartz veins are approached. The SiO_2/CO_2 and SiO_2/total volatiles both show significant decreases as alteration becomes more intense.

Box Mine, Goldfields, Saskatchewan (Precambrian: Archean age). The Box Mine at Goldfields, Saskatchewan is a quartz stockwork localized in a granite sill chiefly in quartzites. Adjacent to and between individual quartz lenses and stringers the granitic rock is highly altered to a quartz-sericite schist.

The analyses shown in Table 55 indicate slight decreases for SiO_2, Na_2O and CO_2 as the veins are approached. Increases are registered by FeO, total Fe, MnO, MgO, K_2O and S. The other constituents show little change or an erratic behaviour.

Table 54. Chemical changes produced by alteration of granite, Red Lake Gold Shore Mine, Red Lake, Ontario

Constituent	Granite*	Carbonate-sericite schist†	Adjusted‡	Gains and losses	Percentage gains and losses
	(%)				
SiO_2	68.1	72.3	72.1	+4.0	+5.9
Al_2O_3	15.1	13.8	13.8	–1.3	–8.6
Fe_2O_3	1.2	0.63	0.63	–0.57	–47.5
FeO	1.8	1.2	1.20	–0.60	–33.3
CaO	2.2	0.83	0.83	–1.37	–62.3
MgO	0.93	0.29	0.29	–0.64	–68.8
Na_2O	4.1	3.0	3.00	–1.10	–26.8
K_2O	3.0	3.0	3.00	+0.00	+0.00
H_2O (total)	0.8	1.2	1.20	+0.40	+50.00
TiO_2	0.42	0.38	0.38	–0.04	–9.5
P_2O_5	0.09	0.03	0.030	–0.06	–66.7
MnO	0.08	0.06	0.060	–0.02	–25.0
CO_2	0.1	0.6	0.60	+0.5	+500.0
S	0.08	0.20	0.20	+0.12	+150.0
C	0.02	0.02			
$O \equiv S$	0.03	0.08			
Total	98.0	97.5			
Specific gravity	2.703	2.696			
	(ppm)				
Li	27	12			
Rb	84	81			
Cs	4.4	1.5			
Cu	15	31			
Ag	<0.5	<0.5			
Au	<0.03	0.6			
Be	<20	<20			
Sr	300	100			
Ba	1000	940			
Zn	60	52			
Cd	<0.5	<0.5			
B	15	38			
U	2	2			
Sn	<15	<15			
Pb	<5	<5			
Zr	150	200			
As	<5	6.5			
Sb	<2	<2			
Bi	<10	<10			
V	30	<10			
Nb	<30	<30			
Se	<2	<2			
Te	0.2	0.2			
Cr	<10	<10			
Mo	1	1			
W	2	2			
F	700	800			
Cl	100	nf			
Co	5	<5			
Ni	5	5			
Pt (ppb)	nf	nf			
Pd (ppb)	<5	<5			
Ratios					
K_2O/Na_2O	0.73	1.0			
SiO_2/CO_2	681	120.5			
SiO_2/H_2O+CO_2+S	69.5	36.2			

Note: nf–not found.

*Composite sample of granite.

†Composite sample of carbonate-sericite schist (0–2 ft from vein).

‡Adjusted % = the percentages of carbonate sericite schist† multiplied by the specific gravity factor 0.997 to reduce to a common volume.

Among the trace elements the following are marked by significant increases as the veins are approached: Cu, Ag, Au, Ba, Zn, Cd, B, Pb, As, Bi, W, Co and Ni. Decreases are registered by Ga, U, Ge, V, Cr and Mo.

There is a gradual increase in the K_2O/Na_2O ratio with increasing intensity of alteration. The SiO_2/CO_2 ratio exhibits a general increase whereas the SiO_2/total volatiles shows a marked decrease in the highly altered zone.

Other deposits in acidic intrusive and extrusive rocks. Numerous gold deposits in granitic and rhyolitic rocks exhibit wall-rock alteration features similar to those just described. A brief review of some significant examples follows:

Moore (1912), in a study of the alteration of a Precambrian granite to quartz-sericite (paragonite) schist at the St. Anthony Gold Mine, Sturgeon Lake, Ontario, found a decrease in the amount of silica as the quartz veins were approached and concluded from the analyses, "... a comparison of the analyses shows a regular decrease in the silica content of the granite indicating a transfer to the veins."

An increase in the Na_2O, Al_2O_3 and iron contents and decreases in CaO, K_2O and S were also evident. The increased soda content was attributed to the formation of the soda mica, paragonite.

At Porcupine, Ontario, Hurst (1935) noted the changes during alteration of quartz porphyry (Pearl Lake porphyry) to quartz-mica schist given in Table 56. Of particular interest is the general loss in SiO_2 and Na_2O and the increase in K_2O, H_2O and S (pyrite) in the altered phase of the porphyry.

Laipanov and Sher (1971) record an extensive investigation of the wall-rock alterations associated with the gold-quartz veins in the Byeryozovsky gold deposit in the Urals. There, the veins containing quartz and sulphides occur in granite dykes, amphibolites and serpentinites of Paleozoic age.

In the granite dykes the alteration zones range from 10 to 25 cm wide and are composed of ankerite, pyrite, sericite and quartz. The alteration zones are characterized by increased contents of SiO_2, Al, Fe, Mg, Mn, K_2O, S, H_2O and decreased contents of Na_2O and Ca as compared to the fresh granite. The minor element content (W, Sn, Bi, Cu, Zn, Pb, Ag, As, Sb, Rb, Li, F) increased as the vein is approached. The gold content also increased from 0.01 to 0.5 ppm. Mica in the altered rocks is characterized by decreasing amounts of Fe^{3+}, Fe^{2+}, and Mg content towards the vein. No general trend in the ankerite composition was observed.

In the amphibolites, consisting of hornblende, oligoclase and sphene, the alteration zones are up to 10 m wide and can be divided into several zones, from an outer to inner as follows: a hornblende-albite-epidote-chlorite-rutile zone; an albite-chlorite-dolomite-rutile-quartz-pyrite zone; and an ankerite-Fe-muscovite-rutile-quartz-pyrite zone. The altered zones are characterized by an increased content of CO_2, H_2O, K_2O, S and a decreased content of Al, Fe, Mg, Ca, Na and SiO_2. The minor element content (Cu, Zn, Pb, Co) decreases. The gold content in the outer zones decreases from 0.015 to 0.008 ppm; that in the inner zones increases up to 0.03 ppm. The iron content in the amphiboles and mica decreases toward the vein; that of the carbonates increases.

In the serpentinites, consisting of serpentine and chromite, the alteration zones are the widest. From the outer to the

Contents

Table 55. Chemical changes produced by alteration of granite, Box Mine, Goldfields, Saskatchewan

Constituents	Granite*	Slightly altered granite†	Adjusted§	Gains and losses of constituents	Percentage gains and losses	Granite*	Highly altered granite‡	Adjusted§	Gains and losses of constituents	Percentage gains and losses
		(%)					(%)			
SiO_2	76.2	74.2	74.4	–1.8	–2.4	76.2	74.3	75.6	–0.6	–0.79
Al_2O_3	12.9	13.7	13.7	+0.8	+6.2	12.9	11.8	12.0	–0.9	–7.0
Fe_2O_3	0.4	0.1	0.1	–0.3	–75.0	0.4	0.4	0.4	–	–
FeO	0.6	1.0	1.0	+0.4	+66.7	0.6	2.7	2.8	+2.2	+366.7
CaO	0.2	0.2	0.2	–	–	0.2	0.2	0.2	–	–
MgO	0.9	0.5	0.5	–0.4	–44.4	0.9	1.4	1.4	+0.5	+55.6
Na_2O	3.8	3.5	3.5	–0.3	–7.9	3.8	3.0	3.1	–0.7	–18.4
K_2O	3.4	4.5	4.5	+1.1	+32.4	3.4	3.9	4.0	+0.6	+17.7
H_2O (total)	0.5	0.3	0.3	–0.2	–40.0	0.5	0.6	0.6	+0.1	+20.0
TiO_2	0.12	0.13	0.13	+0.01	+8.3	0.12	0.12	0.12	–	–
P_2O_5	<0.02	0.02	0.02	–	–	<0.02	<0.02	–	–	–
MnO	<0.02	<0.02	–	–	–	<0.02	0.02	0.02	–	–
CO_2	0.2	<0.1	–	–	–	0.2	<0.1	–	–	–
S	0.14	0.34	0.34	+0.20	+142.9	0.14	1.51	1.54	+1.40	+1000.0
C	<0.1	<0.1				<0.1	<0.1			
O≡S,Cl,F	0.05	0.13				0.05	0.57			
Total	99.5	98.4				99.5	99.4			
Specific gravity	2.640	2.646				2.640	2.687			
				(ppm)						
Li	4	2				4	3			
Rb	105	132				105	115			
Cs	0.5	0.5				0.5	0.4			
Cu	175	25				175	810			
Ag	0.9	<0.3				0.9	5			
Au	0.22	0.02				0.22	16.5			
Be	<2	<2				<2	<2			
Sr	22	30				22	20			
Ba	225	360				225	285			
Zn	12.5	15				12.5	106			
Cd	0.3	<0.3				0.3	1.4			
Hg (ppb)	45	40				45	48			
B	14	88				14	22			
Ga	7.2	5.5				7.2	2.8			
Tl	<2	<2				<2	<2			
Sc	<5	<5				<5	<5			
Y	28	22				28	28			
La	nf	<50				nf	<50			
Th	28	31				28	28			
U	50	6				50	7			
Ge	1.3	1.0				1.3	1.1			
Sn	2.3	1.3				2.3	2.3			
Pb	45	75				45	242			
Zr	215	190				215	207			
As	<10	<10				<10	10			
Sb	<2	<2				<2	<2			
Bi	0.87	<0.5				0.87	4.5			
V	24	<20				24	<20			
Se	<2	<2				<2	2			
Te	<0.2	0.2				<0.2	0.35			
Cr	13	<10				13	<10			
Mo	5	1				5	3.2			
W	3	2				3	3.5			
F	nf	100				nf	100			
Cl	100	100				100	100			
Co	3	4				3	5			
Ni	<1	<1				<1	2			
Pt (ppb)	nf	nf				nf	nf			
Pd(ppb)	nf	nf				nf	nf			
Ratios										
K_2O/Na_2O	0.89	1.29				0.89	1.30			
SiO_2/CO_2	381	>742				381	>743			
SiO_2/H_2O+CO_2+S	90.71	107.54				90.71	34.4			

Note: nf–not found.

*Granite host rock.

†Slightly altered granite (sericite schist) 6 in. from quartz stringers and veins.

‡Highly altered granite (sericite schist) adjacent to quartz stringers and veins (1 in. from veins).

§Adjusted % = percentages of slightly altered granite† and highly altered granite‡ multiplied by the specific gravity factors 1.002 and 1.018 respectively to reduce to a common volume.

Table 56. Chemical changes produced by alteration of quartz porphyry, Porcupine gold area, Ontario*

Constituent	Fresh porphyry†	Altered porphyry‡
	(%)	
SiO_2	63.53	61.56
Al_2O_3	15.68	18.74
Fe_2O_3	1.30	trace
FeO	4.08	0.87
CaO	1.19	2.48
MgO	1.08	1.18
K_2O	2.07	4.00
Na_2O	4.27	2.66
H_2O	1.02	1.85
CO_2	4.42	3.83
TiO_2	0.15	0.41
P_2O_5	0.12	0.18
MnO	0.13	trace
FeS_2 (pyrite)	0.47	2.89
Total	99.51	100.65
Specific gravity	2.760	2.752

Source: Hurst (1935).
*Samples taken in the vicinity of No. 218 vein, 200-foot level, Hollinger Mine.
†Sample typical of the quartz porphyry mass, taken 30 ft from the vein.
‡Waxy phase of altered porphyry from the walls immediately adjoining the vein.

inner zone the following mineral associations can be distinguished: serpentine, talc, magnesite, chromite, dolomite, talc, quartz, pyrite, chromite; and dolomite, quartz, fuchsite. In the altered serpentine rocks the CO_2, Ca and K_2O content decreases, while that of H_2O, Mg, Fe, SiO_2, Al and Na_2O increases. The minor element content (Cu, Zn, Pb) in the outer zones decreases, that in the inner zones increases. Gold content in the altered serpentine decreased from 0.015 to 0.004 ppm.

Laipanov and Sher (1971) concluded that during the process of wall-rock alteration at the Byeryozovsky deposit various exchange reactions take place. Thus, as CO_2, S and K_2O are fixed, SiO_2, Al, Mg and Fe are carried out of the basic and ultrabasic rocks and introduced and precipitated in the altered zones in the granite. H_2O is removed from the serpentinites and supplied to the alteration zones in the granite and amphibolites. Ca is introduced into the altered serpentinites. During the alteration of the basic and ultrabasic rocks Au, Cu, Zn and Pb are removed and partly redistributed. An increase in the concentration of these elements takes place during alteration of the granite. The gold content of the quartz veins can to a considerable degree be related to the extraction of gold from the wall-rocks.

Present day alteration of acidic rocks in the thermal areas of New Zealand has been extensively studied. Some of the waters carry gold in addition to various other elements such as arsenic, antimony and thallium (*see* Chapter II). The thermal waters and their effects on the rocks in the Waiotapu geothermal field have been studied by Healy *et al.* (1963). There, the country rocks are mainly of rhyolitic composition. The chemistry of the waters (steam) is complicated and details should be sought in the original paper. Briefly the waters (steam) are near neutral sulphate-chloride, chloride and bicarbonate-chloride waters containing considerable amounts of constituents such as K, Na, F, B, As, CO_2 and H_2S. At the surface the waters are acid sulphate waters due to surficial oxidation of H_2S. During the alteration of the rhyolitic rocks the quartz is largely inert whereas the magnetite, pyroxene, amphibole and biotite tend to be completely altered. Plagioclase is altered in some sections and relatively unaltered in others. The susceptibility to alteration in decreasing order is: magnetite, pyroxene and hornblende, biotite, plagioclase and quartz. The alteration products are varied, including quartz, opal, hydromica, potash feldspar, albite, wairakite (a zeolite), calcite, pyrite and alunite, the last occurring only in near surface rocks. To generalize, two types of hypogene alteration have been recognized – potassium silicate alteration and albitization associated with the formation of calcite and occasionally with wairakite. Hydromica and K-feldspar are the characteristic minerals of the potassium silicate alteration; these minerals replace the primary soda-lime plagioclase. In more basic rocks, such as andesite, calcite may be associated with the hydromica. The albitization results from the conversion of primary soda-lime plagioclase into albite; this process is commonly associated with the crystallization of calcite and occasionally with the formation of wairakite.

At Waiotapu the zoning of alteration is complex depending on rock types, fissuring and other features. Details should be sought in the original paper by Healy *et al.* (1963). An alteration zoning was also observed by Steiner (1953) at Wairakei in the rhyolitic tuffs and associated sedimentary rocks. Four zones of progressive alteration were distinguished. A superficial zone of sulfuric acid leaching is followed at depth by a zone of argillization. On the zone of argillization is superimposed a zone of zeolitization at shallow depth, and a zone of feldspathization lies at deeper levels.

Summary of wall-rock alteration effects adjacent to gold deposits in acidic (intrusive and extrusive) rocks. The principal types of wall-rock alteration associated with gold deposits in acidic intrusive and extrusive rocks are sericitization, silicification, alunitization and pyritization. Where sericitization and alunitization are marked, there is generally a marked loss of SiO_2 and appreciable gains of H_2O and S. Where silicification is a feature there is often, but not always, an addition of SiO_2. An increase in K_2O and a decrease in Na_2O is common in altered zones in acidic rocks. The Al_2O_3, CaO, MgO and iron oxides show a varied habit. CO_2 is commonly added, especially where carbonatization is extensive. In some wall-rock alteration zones in acidic rocks, however, the intensively sericitized zones next to the quartz veins and lodes are depleted in CO_2.

The ratio K_2O/Na_2O commonly shows an increase with increasing alteration and proximity to gold-quartz veins in acidic rocks, reflecting the extensive development of sericite, potash feldspar, potash-bearing clay minerals or alunite. Where albitization or paragonitization is a feature of the alteration processes the K_2O/Na_2O ratio may remain constant or show a slight decrease. The SiO_2/CO_2 ratio exhibits a variable habit but commonly increases with increase in the intensity of alteration. The SiO_2/total volatiles usually shows a consistent decrease as the veins are approached.

Gold-quartz veins and silicified zones dominantly in sedimentary rocks. Most deposits of this type are quartz veins and lenses dominantly in greywacke quartzite, shale, argillite, phyllite and slate sequences. Some deposits are localized in calcareous shales, argillites and slates. These include two types – stockworks and bedded disseminated deposits.

Gold deposits in sedimentary rocks range in age from

Precambrian to Tertiary. Characteristic examples of the Precambrian type occur in the Yellowknife district, Northwest Territories. There, the deposits are saddle reefs and quartz veins in slates, argillites and greywackes. Similar deposits occur in a number of other Archean gold belts in Canada and elsewhere throughout the world. Paleozoic examples are widespread in Victoria, Australia, particularly in the Bendigo district where the classic deposits are saddle reefs and legs in folded slates and argillites of Ordovician age. Similar deposits occur in the Meguma Group (Ordovician) of Nova Scotia and elsewhere throughout the gold-belts of the world where shales, argillites, slates and greywackes are the host rocks.

Cenozoic gold deposits in sedimentary rocks are relatively common in regions where Tertiary volcanism and hot-spring activity is marked, as in Japan, U.S.S.R., New Zealand and western U.S.A. The bedded disseminated deposits in calcareous shales at Carlin and Cortez in Nevada are of Tertiary age.

Most gold deposits in shales, argillites, phyllites, slates, quartzites and greywackes lack well-defined alteration zones, the quartz veins being more or less frozen against the unaltered rock. Some deposits exhibit a minimal degree of alteration, and a few are marked by characteristic alteration zones.

Yellowknife district, Northwest Territories (Precambrian: Archean age). The majority of quartz veins and pegmatites enclosed by argillites, slates and greywacke in the Yellowknife sedimentary area have no well-defined alteration zones. Some pegmatites and quartz veins, however, are marked along their borders by a development of tourmaline indicating an introduction of boron. A few quartz veins such as those at the Burwash prospect have a thin alteration zone marked by slight bleaching of greywacke on weathered surfaces, caused by the development of sericite and secondary feldspar in the fresh rock. An analysis of a composite sample from this type of alteration zone is given in Table 57. Figure 15 shows the differences graphically.

Table 57. Chemical changes produced by alteration of greywacke, Burwash prospect, Yellowknife, Northwest Territories

Constituent	Composite sample of greywacke	Composite sample of alteration zone	Gains and losses in constituents
		(%)	
SiO_2	62.61	64.48	+1.87
Al_2O_3	16.78	16.22	–0.56
Fe_2O_3	0.38	0.84	+0.46
FeO	5.81	4.95	–0.86
CaO	2.80	0.50	–2.30
MgO	2.99	3.09	+0.10
Na_2O	3.79	3.69	–0.10
K_2O	1.56	2.12	+0.56
H_2O+	1.94	2.77	+0.83
H_2O-	0.12	0.15	+0.03
TiO_2	0.68	0.66	–0.02
P_2O_5	0.16	0.14	–0.02
MnO	0.08	0.06	–0.02
CO_2	0.10	0.00	–0.10
S	0.14	0.20	+0.06
Cl	0.02	0.02	+0.00
Cr_2O_3	0.01	0.03	+0.02
C	0.13	0.10	–0.03
Total	100.10	100.02	–
Less O≡S,Cl	0.06	0.09	–
Net total	100.04	99.93	–
Specific gravity	2.73	2.73	–

The alteration of the greywacke has resulted in the introduction of some silica, water, potash and sulphur and the removal of some alumina, calcium, ferrous iron and carbon dioxide.

At the Ptarmigan deposit, where gold-bearing quartz veins and lenses up to 20 ft thick occur in greywacke, quartzite and slate, the alteration is minimal and not immediately obvious except where narrow zones of black tourmaline border parts of the quartz veins.

The analyses given in Table 58 and graphed in Figure 16 indicate that the chemical effects are localized close to the vein, generally within the zone ranging from 1 to 6 in from the contact. Slight decreases are registered by SiO_2 and Na_2O, and there are small to significant increases in Al_2O_3, total Fe, CaO, MgO, K_2O, H_2O, TiO_2, P_2O_5, CO_2 and S.

Among the trace elements nearly all show an increase as the veins are approached. Marked increases are notable for Cs, Cu, Ag, B, Ga, Sc, As, V, Te, Co, Ni, Zn, Cd, Sn, Pb and W. F shows a significant increase toward the vein; Cl registers a decrease.

It will be noted that there is a general increase in the K_2O/Na_2O ratio and a general decrease in the SiO_2/CO_2 and SiO_2/total volatiles as the gold-quartz veins are approached. It also should be pointed out that the SiO_2/CO_2 ratios in deposits of this type are commonly erratic, and wide fluctuations are frequently encountered, presumably because of the small amounts of CO_2 (carbonatization) present in most deposits.

Argosy Gold Mines, Casummit Lake area, Ontario (Precambrian: Archean age). The Argosy Gold Mine exploited quartz veins in Archean greenstones and a band of greywackes and slates on the north shore of Casummit Lake, Ontario. The minerals present in the veins were essentially quartz with variable amounts of albite, carbonate, arsenopyrite, pyrrhotite, pyrite, chalcopyrite, sphalerite, galena and native gold. Horwood (1938), who studied the wall-rock alteration at this mine, concluded that the alteration took place at two different times: carbonatization related to an early generation of quartz, and sericitization associated with a second generation of quartz. He gives analyses of greywacke, slate and seriticized slate which indicate that during the alteration of the sediments as much as 18 per cent of SiO_2 was lost in the alteration zones some of which are up to 1 ft wide flanking the quartz veins. Other constituents exhibit a variety of changes – potash shows a marked gain, soda a slight increase, sulphur and arsenic marked increases, and carbon dioxide and water decrease.

Caribou Mine, Nova Scotia (Meguma Group: Devonian age). The Caribou Mine is in the Caribou gold district of Nova Scotia about 45 mi northeast of the city of Halifax. The mine was worked by the Consolidated Mining and Smelting Company (Cominco) from 1934 until 1946. The geology is described by Bell (1948).

The orebodies are leg reefs and irregular quartz lenses and stringers in a drag folded zone on the limbs of a fold in quartzites, greywackes and slates of the Meguma Group. The quartz is frozen against the sedimentary rocks, and there are few visible signs of any wall-rock alteration except the

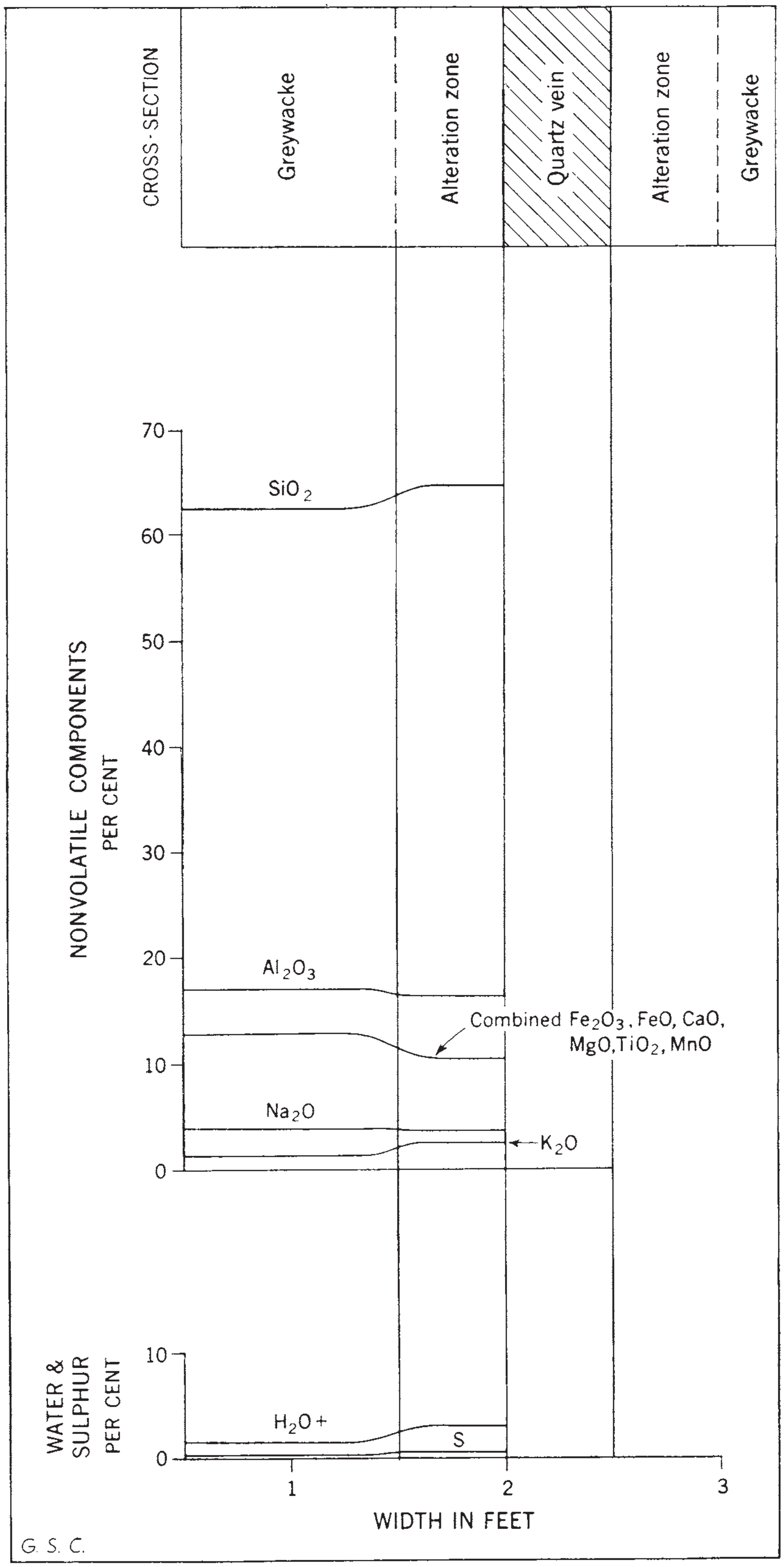

Figure 15. Chemical changes produced by alteration of greywacke, Burwash prospect, Yellowknife, Northwest Territories (*see* Table 57).

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Table 58. Chemical changes produced by alteration of greywacke, Ptarmigan Mine, Yellowknife, Northwest Territories

Constituents	Grey-wacke*	Grey-wacke†	Adjusted‖	Gains and losses	Percentage gains and losses	Grey-wacke*	Grey-wacke‡	Adjusted‖	Gains and losses	Percentage gains and losses	Grey-wacke*	Grey-wacke§	Adjusted‖	Gains and losses	Percentage gains and losses
		(%)					(%)					(%)			
SiO_2	62.9	62.4	63.02	+0.12	+0.191	62.9	53.1	54.91	−7.99	−12.70	62.9	51.3	51.97	−10.93	−17.38
Al_2O_3	16.4	17.8	17.98	+1.58	+9.63	16.4	20.9	21.61	+5.21	+31.77	16.4	22.2	22.49	+6.09	+37.13
Fe_2O_3	1.6	1.3	1.31	−0.29	−18.13	1.6	4.1	4.24	+2.64	+165.0	1.6	1.5	1.52	−0.08	−5.00
FeO	4.8	5.1	5.15	+0.35	+7.29	4.8	4.2	4.34	−0.46	−9.58	4.8	5.7	5.77	+0.97	+20.21
CaO	2.0	1.7	1.72	−0.28	−14.00	2.0	2.7	2.79	+0.79	+39.50	2.0	3.9	3.95	+1.95	+97.50
MgO	3.0	3.1	3.13	+0.13	+4.33	3.0	3.0	3.10	+0.10	+ 3.33	3.0	3.1	3.14	+0.14	+4.67
Na_2O	3.3	2.0	2.02	−1.28	−38.79	3.3	2.8	2.90	−0.40	−12.12	3.3	3.1	3.14	−0.16	−4.85
K_2O	2.2	4.0	4.04	+1.84	+83.64	2.2	2.7	2.79	+0.59	+26.82	2.2	4.5	4.56	+2.36	+107.27
H_2O (total)	1.4	1.9	1.92	+0.52	+37.14	1.4	2.0	2.07	+0.67	+47.86	1.4	2.3	2.33	+0.93	+66.43
TiO_2	0.66	0.69	0.697	+0.037	+5.61	0.66	0.95	0.982	+0.322	+48.79	0.66	1.09	1.10	+0.44	+66.67
P_2O_5	0.16	0.17	0.172	+0.012	+7.5	0.16	0.33	0.341	+0.181	+113.13	0.16	0.16	0.162	+0.002	+1.25
MnO	0.07	0.06	0.061	−0.009	−12.86	0.07	0.10	0.103	+0.033	+47.14	0.07	0.07	0.071	+0.001	+1.43
CO_2	<0.1	<0.1				<0.1	0.10	0.103			<0.1	0.1	0.101		
S	0.06	0.42	0.424	+0.364	+606.7	0.06	0.96	0.993	+0.933	+1555	0.06	1.56	1.58	+1.52	+2533
Total	98.6	100.7				98.6	97.7				98.6	100.1			
Specific gravity	2.756	2.783				2.756	2.850				2.756	2.792			
						(ppm)									
Li	52	45				52	51				52	54			
Rb	68	33				68	72				68	80			
Cs	4	4				4	21				4	14			
Cu	47	69				47	157				47	237			
Ag	<0.4	<0.4				<0.4	<0.4				<0.4	1.6			
Au	0.02	0.07				0.02	0.13				0.02	8.5			
Be	<2	<2				<2	<2				<2	<2			
Sr	340	210				340	280				340	390			
Ba	440	1000				440	520				440	720			
Zn	81	148				81	316				81	474			
Cd	1.3	1.3				1.3	1.9				1.3	14.4			
Hg (ppb)	4	4				4	7				4	6			
B	30	50				30	1300				30	20			
Ga	14	17				14	18				14	19			
In	<0.5	<0.5				<0.5	<0.5				<0.5	<0.5			
Tl	<1	<1				<1	<1				<1	<1			
Sc	13	15				13	24				13	31			
Y	<20	<20				<20	<20				<20	<20			
Yb	<4	<4				<4	<4				<4	<4			
U	0.7	1.2				0.7	0.8				0.7	1.7			
Ge	<0.5	0.55				<0.5	0.92				<0.5	<0.5			
Sn	1.2	18				1.2	16				1.2	7.6			
Pb	17	76				17	195				17	424			
Zr	160	170				160	190				160	220			
As	6	88				6	3500				6	50			
Sb	1	2				1	2				1	3			
Bi	<0.5	<0.5				<0.5	<0.5				<0.5	1.8			
V	150	170				150	210				150	250			
Se	nf	nf				nf	nf				nf	nf			
Te	<0.2	0.5				<0.2	1.0				<0.2	1.0			

Mo	1	4	1	2	1	2
W	<2	2	<2	2	<2	4
F	325	599	325	827	325	713
Cl	300	100	300	200	300	100
Co	23	26	23	31	23	25
Ni	66	65	66	98	66	79
Pt (ppb)	<30	<20	<30	<20	<30	<60
Pd (ppb)	<4	<2	<4	4	<4	<8
Ratios						
K_2/Na_2O	0.7	2.0	0.7	1.0	0.7	1.5
SiO_2/CO_2	>629	>624	>629	531	>629	513
SiO_2/H_2O+CO_2+S+As	41.6	26.2	41.6	15.6	41.6	13.0

Note: nf–not found. Numbers in parentheses refer to sample in Figure 16.

*Composite chip sample of greywacke 2 to 35 ft from vein, Ptarmigan Mine (1).

†Composite chip sample of greywacke 6 to 18 in. from vein, Ptarmigan Mine (2).

‡Composite chip sample of greywacke 1 to 6 in. from vein, Ptarmigan Mine (3).

§Composite chip sample of greywacke at vein contact, Ptarmigan Mine (4).

‖Adjusted % = percentages of greywacke‡ and greywacke§ multiplied by the specific gravity factors 1.010, 1.034 and 1.013 respectively to reduce to a common volume.

development of a selvage of chlorite in places and a general dissemination of arsenopyrite and pyrite outward from the vein for 1 ft or so. This dissemination of arsenopyrite near gold-bearing saddle reefs, legs and irregular lenses of quartz is common in all of the gold deposits of the Meguma Group in Nova Scotia and in fact is common in practically all gold-quartz veins in sequences of greywackes, quartzites, slates and argillites.

As shown by the analyses in Table 59 there is a slight loss of SiO_2, H_2O and MnO as the veins are approached and significant gains of Al_2O_3, Fe_2O_3, FeO, total Fe, CaO, MgO, TiO_2, P_2O_5, CO_2 and S. Na_2O exhibits little change whereas K_2O shows a significant increase.

The trace elements have a rather erratic behaviour, but general increases are registered by Rb, Cs, Ag, Au, Sr, Ba, Zn, Sc, Y, U, Zr, As, V, Cr and Mo. Li and Co show a slight decrease as the vein is approached. Cu, Cd, Hg and Ni are particularly erratic. F increases toward the vein; Cl shows no tendency in this direction.

Lena goldfields, Bodaibo synclinorium, U.S.S.R. (Upper Proterozoic age). In this field the country rocks are Upper Proterozoic polymict sandstones and schistose siltstones falling into the greenschist facies. For the auriferous quartz veins in sandstones Konovalov (1973) found the alteration zonation to be as follows: (1) virtually unaltered rocks composed of quartz, carbonates (dolomite, siderite), plagioclase (andesine, albite), sericite and chlorite and lesser amounts of microcline, pistacite (epidote) and hornblende; (2) slightly altered rocks (2–5 m from vein contacts) with the same mineralogy as above with the omission of chlorite, pistacite and hornblende; (3) highly altered rocks composed mainly of quartz, ankerite, calcite and sericite; and (4) auriferous quartz veins.

Material balance calculations show that during alteration SiO_2 and Na_2O have been leached and K_2O and CO_2 introduced. The other components registered little change. Konovalov (1973) concluded that the silica migrated into the fissure cavities where it crystallized as quartz.

Muruntau deposit, Uzbek, S.S.R. (Paleozoic age). The Muruntau deposit is an en echelon system of thick gold-bearing quartz veins, bordered by stockworks of gold-bearing quartz-sulphide stringers and veins. The host rocks are calcareous siltstones, shales and various types of schists, all of Paleozoic age. The wall-rock alteration associated with this deposit is discussed in detail by Rakhmatullaev and Sher (1969) and Baimukhamedov *et al.* (1975). A short description of the orebodies is given in the descriptions of deposits in this chapter.

The alteration in the Muruntau deposit is considerably different than that found in most gold deposits in sedimentary rocks. Briefly, it is a skarn type of alteration on which is superimposed a quartz-microcline metasomite.

An early preore alteration of the country rocks is the most widespread. During this stage the chlorite-sericite aggregate of the matrix of the siltstone was converted into a mass of fine flaky biotite, and rocks originally rich in carbonate are marked by developments of actinolite and less often of pyroxenes. The altered rocks have more compact structures than the primary ones and are marked by a conchoidal fracture. Also typical of these rocks is a banded coloration due

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Table 59. Chemical changes adjacent to gold-quartz orebodies, Caribou Mine, Caribou gold district, Nova Scotia

Constituent	Quartzite*	Quartzite†	Adjusted**	Gains and losses	Percentage gains and losses	Quartzite*	Quartzite‡	Adjusted	Gains and losses	Percentage gains and losses	Quartzite*	Quartzite§
		(%)					(%)					(%)
SiO_2	77.8	71.4	72.3	–5.5	–7.1	77.8	72.7	73.0	–4.8	–6.2	77.8	73.0
Al_2O_3	10.8	11.0	11.1	+0.3	+3.1	10.8	11.2	11.2	+0.4	+3.7	10.8	11.6
Fe_2O_3	0.5	0.6	0.6	+0.1	+21.4	0.5	0.5	0.5			0.5	0.5
FeO	1.7	2.9	2.9	+1.2	+70.6	1.7	2.8	2.8	+1.1	+64.7	1.7	2.9
CaO	0.4	1.8	1.8	+1.4	+350.	0.4	1.8	1.8	+1.4	+350.	0.4	1.8
MgO	0.8	1.1	1.1	+0.3	+37.5	0.8	1.1	1.1	+0.3	+37.5	0.8	1.1
Na_2O	2.8	2.7	2.7	–0.1	–3.6	2.8	2.6	2.6	–0.2	–7.1	2.8	2.6
K_2O	1.5	2.2	2.2	+0.7	+46.7	1.5	2.2	2.2	+0.7	+46.7	1.5	2.3
H_2O (total)	1.4	1.2	1.2	–0.2	–14.3	1.4	1.2	1.2	–0.2	–14.3	1.4	1.3
TiO_2	0.61	0.64	0.65	+0.04	+6.6	0.61	0.63	0.63	+0.02	+3.3	0.61	0.66
P_2O_5	0.05	0.27	0.27	+0.22	+440.	0.05	0.14	0.14	+0.09	+180.	0.05	0.28
MnO	0.17	0.13	0.13	–0.04	–23.5	0.17	0.13	0.13	–0.04	–23.5	0.17	0.13
CO_2	0.1	2.5	2.5	+2.4	+2400.	0.1	2.7	2.7	+2.6	+2600.	0.1	2.7
S	<0.02	0.18	0.18			<0.02	0.18	0.18			<0.02	0.12
C												
O≡Cl,F,S,	0	0.08	0.08			0.	0.08	0.08			0	0.06
Total	98.6	98.6				98.6	99.8				98.6	101.0
Specific gravity	2.706	2.738				2.706	2.718				2.706	2.945
							(ppm)					
Li	27	20				27	19				27	19
Rb	65	90				65	88				65	89
Cs	2.6	3.6				2.6	3.4				2.6	3.7
Cu	36	4				36	23				36	25
Ag	0.7	0.9				0.7	1.0				0.7	1.1
Au	<0.01	0.01				<0.01	0.01				<0.01	0.01
Sr	130	160				130	170				130	170
Ba	280	390				280	400				280	410
Zn	37	43				37	45				37	41
Cd	1.9	1.4				1.9	1.2				1.9	1.4
Hg (ppb)	25	15				25	19				25	22
B	15	10				15	16				15	16
Ga	16	15				16	14				16	15
Sc	12	14				12	13				12	12
Y	<20	<20				<20	21				<20	30
Yb	<4	<4				<4	<4				<4	<4
U	0.1	0.1				0.1	0.3				0.1	<0.1
Pb	20	20				20	20				20	20
Zr	380	290				380	340				380	360
As	15	1250				15	1250				15	1500
Sb	<1	<1				<1	<1				<1	<1
Bi	<0.2	<0.2				<0.2	<0.2				<0.2	<0.2
V	43	51				43	53				43	60
Se	nd	nd				nd	nd				nd	nd
Te	<0.5	<0.5				<0.5	<0.5				<0.5	<0.5
Cr	43	62				43	55				43	48
Mo	1	1				1	1				1	3
W	<2	<2				<2	<2				<2	<2
F	<200	300				<200	200				<200	200
Cl	<200	<200				<200	<200				<200	200
Co	20	20				20	18				20	18
Ni	26	26				26	26				26	26
Pt	nd	nd				nd	nd				nd	nd
Pd	nd	nd				nd	nd				nd	nd
Ratios												
K_2O/Na_2O	0.54	0.81				0.54	0.85				0.54	0.88
SiO_2/CO_2	778.0	28.56				778.0	26.93				778.0	27.04
SiO_2/H_2O+CO_2+ S+As	51.47	17.83				51.47	17.29				51.47	17.10

Note: nd–not detected.

*Composite chip sample of quartzite and greywacke, 1–50 ft from vein.

†Composite chip sample of quartzite and greywacke, 10–12 in. from vein.

‡Composite chip sample of quartzite and greywacke, 7–10 in. from vein.

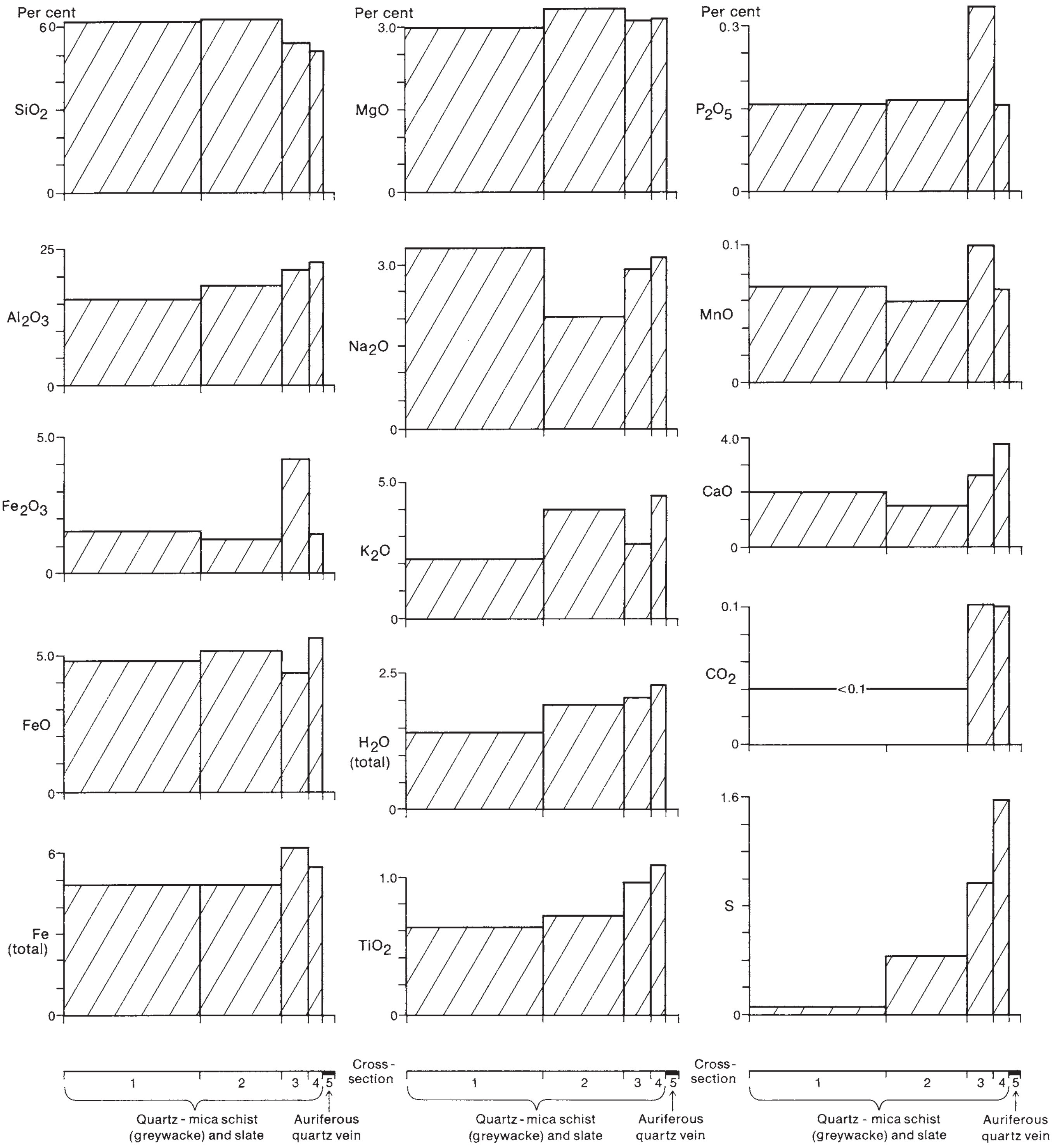
§Composite chip sample of quartzite and greywacke, 5–7 in. from vein.

||Composite chip sample of quartzite and greywacke, 3–5 in. from vein.

¶Composite chip sample of quartzite and greywacke, 1–3 in. from vein.

** Adjusted % = percentages of quartzite†, quartzite‡, quartzite§, quartzite||, and quartzite¶ multiplied by the specific gravity factors 1.012, 1.004, 1.088, 1.014 and 1.017 respectively to reduce to a common volume.

Adjusted**	Gains and losses	Percentage gains and losses	Quartzite*	Quartzite‖	Adjusted**	Gains and losses	Percentage gains and losses	Quartzite*	Quartzite¶	Adjusted**	Gains and losses	Percentage gains and losses
(%)				(%)					(%)			
79.4	+1.6	+2.1	77.8	71.3	72.3	−5.5	−7.1	77.8	70.3	71.5	−6.3	−8.1
12.6	+1.8	+16.7	10.8	10.8	11.0	+0.2	+1.9	10.8	11.9	12.1	+1.3	+12.0
0.5			0.5	0.6	0.6	+0.1	+20.0	0.5	0.2	0.2	−0.3	−60.0
3.2	+1.5	+88.2	1.7	2.9	2.9	+1.2	+70.6	1.7	2.9	3.0	+1.3	+76.5
2.0	+1.6	+400.	0.4	1.9	1.9	+1.5	+375.	0.4	1.9	1.9	+1.5	+375.
1.2	+0.4	+50.0	0.8	1.1	1.1	+0.3	+37.5	0.8	1.1	1.1	+0.3	+37.5
2.8			2.8	2.7	2.7	−0.1	−3.6	2.8	2.7	2.8		
2.5	+1.0	+66.7	1.5	2.2	2.2	+0.7	+46.7	1.5	2.2	2.2	+0.7	+46.7
1.4			1.4	1.1	1.1	−0.3	−21.4	1.4	1.1	1.1	−0.3	−21.4
0.72	+0.11	+18.0	0.61	0.65	0.66	+0.05	+8.2	0.61	0.65	0.66	+0.05	+8.2
0.31	+0.26	+520.	0.05	0.32	0.32	+0.27	+540.	0.05	0.32	0.33	+0.28	+560.
0.14	−0.03	−17.6	0.17	0.13	0.13	−0.04	−23.5	0.17	0.13	0.13	−0.04	−23.5
2.9	+2.8	+2800.	0.1	2.7	2.7	+2.6	+2600.	0.1	3.0	3.1	+3.0	+3000.
0.13			<0.02	0.20	0.20			<0.02	0.18	0.18		
0.07			0	0.09	0.09			0	0.08	0.08		
			98.6	98.5				98.6	98.5			
			2.706	2.743				2.706	2.753			
						(ppm)						
			27	22				27	23			
			65	89				65	90			
			2.6	3.7				2.6	3.6			
			36	<4				36	8			
			0.7	1.4				0.7	1.3			
			<0.01	0.01				<0.01	0.01			
			130	170				130	180.			
			280	420				280	480.			
			37	41				37	43			
			1.9	2.1				1.9	1.7			
			25	18				25	20			
			15	13				15	15			
			16	15				16	15			
			12	14				12	11			
			<20	<20				<20	21			
			<4	<4				<4	<4			
			0.1	0.5				0.1	0.5			
			20	25				20	20			
			380	380				380	550			
			15	1500				15	1500			
			<1	<1				<1	<1			
			<0.2	<0.2				<0.2	<0.2			
			43	50				43	56			
			nd	nd				nd	nd			
			<0.5	<0.5				<0.5	<0.5			
			43	60				43	40			
			1	2				1	2			
			<2	<2				<2	<2			
			<200	300				<200	200			
			<200	<200				<200	<200			
			20	16				20	19			
			26	24				26	29			
			nd	nd				nd	nd			
			nd	nd				nd	nd			
			0.54	0.81				0.54	0.81			
			778.0	26.41				778.0	23.43			
			51.47	17.18				51.47	15.87			



Numbers on cross-section refer to samples described in Table 58

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Figure 16. Chemical changes produced by alteration of greywacke, Ptarmigan Mine, Yellowknife, Northwest Territories. (Numbers on cross-section refer to samples described in Table 58.)

to the presence of brown biotite-rich, green actinolite-rich, and grey quartz-rich bands.

This skarn-type alteration has been interpreted as a contact metamorphic phenomenon (conversion of rocks into hornfels) related to an assumed granitoid intrusive body concealed at some depth.

A comparison of the mineral and chemical compositions of the initial and altered rocks reveals that the latter are marked by gains in the contents of magnesium, iron, alkali metals and partly aluminum. Carbon dioxide and calcium were lost from the calcareous rocks during the alteration processes. Silica was apparently redistributed; it shows losses in the initial aluminous rocks and gains in the altered limy rocks. The composition of newly formed pyroxenes are interesting. The pyroxene at shallow depths is diopside; at depths of 150 to 200 m, salite; and from 400 m downward, clinoenstatite. This indicates that the Fe and Mg contents of pyroxene increase depthwise. The only ore element introduced during this period was tungsten, precipitated as scheelite.

Superimposed on the hornfels are quartz-microcline metasomatites developed principally along the contacts of most gold-bearing and sulphide-bearing quartz veins and veinlets. This bordering alteration zone is 2 to 3 cm wide in most places and wider locally.

The quartz-microcline metasomatite is a fine-grained (0.02–0.04 mm) light pink rock consisting of quartz (35–50%), fine-grained microcline (25–50%), commonly replacing biotite, variable amounts of calcite (0.5%; occasionally up to 10%) and apatite (up to 9%). Relict minerals include rutile, leucoxene and zircon. The apatite is haloid free (hydroxylapatite). The enhanced apatite content of the metasomatites is attributed to the presence of phosphorite beds in the host rocks.

A comparison of the compositions of biotitized and actinolitized siltstone (hornfels) with that of the quartz-microcline metasomatites shows that during the formation of the metasomites, SiO_2, Ca, K and CO_2 were introduced and Al, Fe, Mg, Na and H_2O were removed from the hornfels.

The quartz-microcline metasomatites are associated with numerous stringers of biotite, amphibole and pyroxene, all cutting the quartz veins. They have a length of a few metres and their thickness ranges from 1.0 to 1.5 cm. Commonly they have a very irregular shape. The mineral composition of these stringers is the same as the metamorphic rocks they intersect.

Reefton gold lodes, New Zealand (Precambrian or Paleozoic). The Reefton lodes in South Island, New Zealand are quartz veins and stockworks in faults, sheared and crushed zones, and fractures cutting Waiuta Series greywacke, quartzite and phyllite. The mineralization of the quartz bodies includes native gold, pyrite, stibnite, arsenopyrite, chalcopyrite, molybdenite, calcite and rare galena (Gage, 1948).

Near the veins and in the stockworks the greywacke and phyllite are altered to a soft light-coloured rock composed mainly of quartz, sericite, pyrite, arsenopyrite and carbonate. The unaltered greywacke consists chiefly of quartz, feldspar and chlorite; of these minerals the feldspar and chlorite are replaced mainly by sericite and carbonate in the alteration zones. Henderson (1917) gives analyses of the altered and unaltered greywacke and argillite (phyllite), which show little change as alteration proceeds. There is a general loss of silica, in altered zones in greywacke as much as 7 per cent and a general increase in potash as the veins are approached.

Carlin gold deposit, Nevada (Tertiary age). This deposit is one of a number of disseminated bedded deposits in the Carlin district of Nevada. It serves as an example of the type of alteration present in these deposits.

The Carlin deposit is characterized by large disseminated replacement-type ore bodies in the upper beds of the Silurian Roberts Mountains Formation. (*See* the more detailed description of this and similar orebodies in the section on description of deposits in this chapter.) Radtke *et al.* (1972*a*) have described the alteration effects attendant upon mineralization in the Carlin deposit in some detail.

The host rocks for the orebodies are dark- to medium-grey, thin bedded, siliceous, argillaceous, dolomitic limestones containing widely varying amounts of calcite, dolomite, illite and quartz, plus minor kaolin, montmorillonite(?), chlorite, K-feldspar, plagioclase, pyrite, zircon, barite, rutile, sphene and carbonaceous materials.

The primary gold ores are composed of widely varying amounts of quartz, illite, calcite, dolomite and barite, the same minor accessory minerals as are present in the host rocks, plus pyrite, pyrrhotite, arsenopyrite, realgar, orpiment, stibnite, chalcopyrite, sphalerite, galena, cinnabar, molybdenite and several sulphosalt minerals.

The analyses given by Radtke *et al.* (1972*a*) show that the most important change in the rocks during mineralization was the removal of Ca, Mg, CO_3 and the introduction of SiO_2. Aluminum exhibits an enrichment as does also iron, the latter reflecting the introduction of pyrite and smaller amounts of pyrrhotite and arsenopyrite. In addition to SiO_2 and Fe the following elements exhibit significant enrichments in the ores compared with the host rock: Ba(2200 ppm), As(480 ppm), Zn(185 ppm), Sb(130 ppm), B(70 ppm), Cu(35 ppm), Pb(30 ppm), La(30 ppm), Hg(25 ppm), W(18 ppm?), Au(11 ppm), Mo(7 ppm), Se(2 ppm?) and Ag(0.4 ppm?). Approximate enrichment factors for these elements in the primary ores *vs.* the fresh host rocks are Au(>550X), Hg(>300X), Sb(160X), As(>50X), Ba(15X), Zn(13X), B(5X), Mo(>4X), Pb(>4X) and Se(>2X). Ag, W and La are also enriched, but the data sets available preclude the calculation of meaningful enrichment factors.

Other deposits in sedimentary rocks. There are a number of important gold deposits in sedimentary rocks that are especially difficult to classify with respect to wall-rock alteration effects. Some of these have skarn characteristics; others have high-grade metamorphic features. Examples are the Homestake Mine, Madsen Mine, Morro Velho Mine and others.

Gustafson (1933) and Slaughter (1968) describe the wall-rock alteration effects attending the great auriferous quartz lodes in the Homestake Mine at Lead, South Dakota. There, the host rocks (Homestake Formation) are cummingtonite schists bearing garnet, biotite and chlorite, probably derived from a sandy, clayey iron-magnesium carbonate sediment (sideroplesite). Near the quartz orebodies the cummingtonite schists, and in places the sideroplesite schists, are converted to rocks containing essentially chlorite, ankerite, arsenopyrite, pyrrhotite and pyrite. The strongly chloritized rock is generally auriferous. The mineralization stages are complex and are described in more detail in the section on description of deposits in this chapter.

The orebodies of the Madsen Mine in the Red Lake district of Ontario are in silicified, sulphide-bearing (pyrite, pyrrhotite and arsenopyrite) tuffs in which abundant garnets are developed near the orebodies but seldom in the ore. At depth there are orebodies in actinolite schists, which are remarkably low in quartz. Further details are given in the section on descriptions of deposits in this chapter.

The Morro Velho Gold Mine and other similar deposits in the Quadrilátero Ferrífero, Minas Gerais, Brazil are characterized by unusual types of wall-rock alteration that have been variously interpreted. The alteration at the Morro Velho has been called "Lapa Sêca" and consists of an uneven envelope of rock composed essentially of ankerite, albite and quartz with pyrite and pyrrhotite. Some investigators consider this rock to be part of a recrystallized iron-formation. Further details are given in the section on description of deposits in this chapter.

Coarse-grained gold-quartz veins with a pegmatitic aspect in high-grade metamorphic sedimentary schists and gneisses commonly grade imperceptibly into these metamorphic rocks or are frozen against walls of schist and gneiss. In many places a selvage or diffuse zone of tourmaline and/or mica is characteristic; in other places garnet, andalusite, staurolite, cordierite and even corundum may be developed both in the veins and adjacent wall rocks. Such veins are common in the Yellowknife Group sediments and in similar rocks on Outpost Islands, Great Slave Lake, Northwest Territories (Hawley, 1939; Lord, 1951).

Summary of wall-rock alteration effects adjacent to (gold deposits in sedimentary rocks). In greywacke, quartzite, argillite and slate sequences the wall-rock alteration effects are minimal. Commonly there is a slight desilication close to the vein and a development of chlorite and some sericite. Na_2O is usually leached and K_2O added. As the veins are approached increases in As, S, P_2O_5, B and CO_2 are characteristic.

Where gold deposits are developed in limestones, and calcareous quartzite, greywacke and slates marked alteration effects are noted – at Muruntau a skarn-type alteration with a superimposed quartz-microcline metasomite has developed, and in the Carlin-type deposits an extensive silicification, removal of CO_2 and characteristic additions of S, As, Sb, Hg and a host of other chalcophile elements are evident.

> Auriferous veins or deposits may be of any form, may occur in any rock, and may have received their gold from various sources.
> – J. M. Maclaren, 1908

Descriptions of typical gold deposits

The following descriptions treat gold deposits according to the classification outlined at the beginning of this chapter. Typical examples are described, but the descriptions are not detailed. Sufficient references are given, however, to enable the interested reader to pursue the details of each type of deposit in depth. Supplementary references to many of the deposits mentioned are included in the Selected bibliography.

Auriferous porphyry dykes, sills and stocks; auriferous coarse-grained granitic bodies, aplites and pegmatites

The indigenous gold content of these granitic rocks is invariably low as shown by analyses of a variety of types done in our laboratories (Table 60).

Table 60. Gold and silver content of fresh (unmineralized) granitic rocks

Rock type	Au average	Au average	Ag average	Ag
	(ppm)	(oz/ton)	(ppm)	(oz/ton)
Pegmatites	0.003	0.00009	0.05	0.0015
Coarse-grained granitic rocks	0.003	0.00009	0.05	0.0015
Quartz-feldspar porphyry	0.017	0.0005	0.1	0.003
Quartz-feldspar porphyry with indigenous pyrite	0.10	0.003	1.0	0.03

We conclude from these data that normal pegmatites, coarse-grained granites and porphyries cannot be considered potential economic sources for gold and silver. Such bodies may, however, be greatly enriched in both elements where they are sheared, faulted, fractured and otherwise structurally prepared, permitting the localization of quartz veins, silicified and pyritized zones and disseminations. Such granitic bodies occur throughout the world, and some constitute large gold deposits. They are described in category 6 below. A few pegmatites, coarse-grained granites and porphyries contain gold in commercial quantities that the earlier investigators attributed mainly to magmatic segregation processes within the bodies. A few of these are described briefly below.

Weed (1904*a*) summarizes numerous observations made with respect to the presence of gold as a primary constituent of eruptive (igneous) rocks. These include aplites, diorites, basalts and diabase in which he thinks the gold may have been of primary origin. In a later paper he (Weed, 1904*b*) refers to auriferous and argentiferous basaltic (monchiquite) dykes from the Krynka River area in eastern Russia. These dykes consist essentially of augite, biotite, hornblende and olivine in a glassy base. The auriferous dykes are especially rich in fluorite (up to 2.5%) and abundant pyrite. Brock (1904) also records the presence of gold, apparently primary, in a porphyry dyke from the North Fork of the Salmon River in British Columbia.

Lacroix (1922–1923) mentions several occurrences of gold, some with associated hematite, others in quartz in pegmatites in Madagascar, and Spurr (1906, 1923) asserts that gold occurs in quartz pegmatites (alaskites) in Alaska, at Silver Peak, Nevada and elsewhere. Butler *et al.* (1920) describe an unusual veinlike deposit from Gold Hill, Utah that contains native gold in an intergrown mass of quartz, orthoclase, fibrous amphibole, epidote, magnetite, carbonate, tourmaline, powellite, malachite, scheelite, molybdenite and apatite. Knopf (1924) mentions quartz-microcline-tourmaline-mica dykes or veins near Rochester, Nevada that carry coarse native gold, arsenopyrite and pyrite.

The Natas Mine in South-West Africa (Reuning, 1925) is in pegmatite dykes and quartz veins in the apex of a granitic stock. The gold in the pegmatite dykes is probably related to the quartz vein stage rather than to the pegmatite stage. It is associated with scheelite, molybdenite and copper sulphides.

Brammall (1926) mentions the presence of gold (and silver) in two places in the Dartmoor granite, southwest England. Judging from the occurrence of the visible metal as inclusions in both quartz and feldspar, and from the presence of both gold and silver in biotite, he inferred that the two metals were of primary origin. There are, however, quartz stringers in the vicinity of the occurrences suggesting that some of the gold may be introduced. Native gold has also been observed in pegmatites on Dartmoor (Brammall and Harwood, 1924). In the Bittleford pegmatite it occurs as specks and spangles embedded in feldspar and quartz. Associated minerals of interest are tourmaline, ilmenite, apatite and pyrrhotite.

An unusual type of gold deposit in an igneous body occurred on the farm Waaikraal, about 25 mi northeast of Rustenburg. According to Wagner (1927) the gold ore is a magmatic segregation in a sill belonging to the Bushveld Complex. The sill is a pyroxenitic quartz gabbro merging into a pegmatitic quartz gabbro and pegmatitic quartz monzonite enclosing slivers of a banded magnetite-augite rock, which is probably a recrystallized ironstone of sedimentary origin (iron-formation). Having regard to the common occurrence of gold and gold deposits in iron-formations one wonders if this is not simply a case of reconstitution and concentration of gold from the iron-formation induced by magmatic activity.

Shenon and Reed (1934) describe fractured and brecciated pegmatitic material in a shear zone at Orogrande, Idaho County, Idaho that contains quartz, pyrite and gold. Gallagher (1940) mentions a number of occurrences of gold in pegmatite and in quartz bodies containing feldspars.

In the Canadian Malartic Mine in the Malartic district of Quebec, Cooke (1946) mentions that pegmatite veins carrying gold have been found within a porphyry mass. These are commonly much richer than the average siliceous ore of the mine. The veins (pegmatites) consist of quartz intergrown in places with albite, and contain a large assortment of other minerals such as biotite, muscovite, fluorite, rutile, tourmaline, molybdenite, pyrite, chalcopyrite and native gold. Cooke thought that occurrences of such veins (pegmatites) indicated that the gold deposits originated in part from the known bodies of porphyry, and perhaps in part from similar bodies consolidating at greater depths.

Indigenous pyrite, pyrrhotite and arsenopyrite from pegmatites generally contain only traces of gold and silver according to Geological Survey analyses. There are, however, references in the literature to the fact that these sulphides as well as others are often auriferous, values up to 0.1 oz Au/ton and more being reported. It is generally not stated whether these sulphides were original or not; in most places they appear to have been introduced after the consolidation of the pegmatitic bodies.

The descriptions of many gold lodes in pegmatites and granitic rocks indicate that the gold mineralization is usually unrelated to the (magmatic) crystallization stage. The sequence of events is generally the introduction and consolidation of the granitic body followed much later by a number of stages of fracturing, faulting, shearing, alteration and introduction of sulphides, quartz and native gold. A number of examples exhibiting this sequence of events are described in a later section.

Auriferous skarn-type gold deposits

Gold is a frequent constituent of skarn deposits, in which it is commonly more abundant than the literature would indicate. Most skarn deposits yield gold as a byproduct of copper and lead-zinc mining, but there are a number of these deposits that are greatly enriched in gold and silver and are mined essentially for the two precious metals.

The general features of skarn deposits are well known and need not be described in detail here. Most of the deposits occur in highly metamorphosed terranes in which there has been much granitization and injection of granitic rocks. Some deposits occur near the contacts of granitic rocks and have long been called 'contact metamorphic' (Fig. 9); others are developed in favourable reactive beds or zones some distance from granitic contacts.

Most of the gold deposits occur in irregular skarn zones or are associated with skarn minerals developed in limestones, dolomites, carbonate-bearing shales or carbonate-bearing schists. The deposits are irregular and bunchy in form, but many are tabular, following beds that have been selectively replaced. The gold ore shoots in most deposits are commonly highly irregular, their limits being generally only determined by assay methods.

The deposits usually contain a characteristic suite of relatively high temperature Ca-Mg-Fe-silicates such as garnet, epidote, vesuvianite, diopside, tremolite, scapolite, wollastonite and axinite. A lower temperature suite of minerals is also commonly present including serpentine, phlogopite, muscovite, quartz, calcite, dolomite and various sulphides, mainly chalcopyrite, bornite, chalcocite, pyrite, pyrrhotite, arsenopyrite, galena, sphalerite, molybdenite and locally various Ni-Co sulphides and arsenides. Magnetite and hematite occur in many of the deposits and scheelite in a few. Stibnite is rare in most deposits, but occurs in quantity in those of the Bau mining district in Sarawak. The gold minerals include native gold, rarely electrum, and in places various tellurides. Aurostibite has not been reported from skarns.

The elements commonly accompanying gold in skarn deposits are Fe, S, Cu, Ag, Zn, Cd, B, Ga, Ge, Sc, Y, rare-earths, Th, U, Pb, Ti, P, As, (Sb), Bi, Se, Te, Mo, W, (F), (Cl), (Co), (Ni) and (Pt metals). Those in parentheses are relatively rare in deposits enriched in gold. The elements most frequently enriched with gold in skarn deposits are Fe, S, Cu, Ag, Zn, Pb, Mo, As, Bi and Te. There is commonly a positive correlation between Au and Cu in some skarn deposits. Tungsten is a common trace element in gold-bearing skarn deposits. The element belongs to the early phase of skarnification, whereas gold tends to be precipitated late in the mineralization processes. The two elements may, therefore, be negatively correlated, for it is common to find skarn deposits that are rich in tungsten (scheelite) practically devoid of gold and vice versa.

Skarn-type gold deposits have a widespread distribution throughout the world especially in belts of carbonate rocks invaded by diorites, monzonites, granodiorites and granites. Among these gold is particularly enriched in those containing relatively large amounts of arsenopyrite and pyrite. Skarn-type deposits rich in copper, or in copper, lead and zinc, generally carry a little gold and silver. Skarn-type iron deposits containing magnetite, titan-magnetite, and hematite, and the various skarn deposits enriched in tungsten (scheelite), tin (cassiterite), graphite or platinum, generally carry only traces of gold and silver. A few typical examples of skarns enriched in gold are described below:

In the Hedley district of British Columbia two large gold deposits were developed in skarn (Camsell, 1910; Billingsley and Hume, 1941; Dolmage and Brown, 1945) – The Nickel Plate Mine (Lamb *et al.*, 1957) and the French Mine (Lamb, 1957). These two mines worked orebodies developed in skarn near the contact of Cretaceous granodiorite and Triassic limestone, limy argillite, quarztite and tuffs and volcanic flows. In the Nickel Plate area numerous porphyritic gabbro, dioritic and other dykes and sills cut the country into blocks; this effect was not notable in the French Mine. The orebodies occurred all within the skarn and were tabular, pipelike and irregular. In the Nickel Plate Mine the principal mineral was gold-bearing arsenopyrite, often present in massive shoots. Other minerals included chalcopyrite, pyrrhotite and tetradymite. The ore in the French Mine was mainly skarn impregnated with small amounts of gold, bornite, chalcopyrite, pyrrhotite, molybdenite, chalcocite, covellite, safflorite, cobaltite, native bismuth and two tellurides, hedleyite and joseite. The grade of the two mines was approximately 0.4 Au oz/ton (13.7 ppm) and 0.035 Ag oz/ton (1.19 ppm), and the Au/Ag ratio ranged from 4 to 10 in the ores. The copper content averaged 0.04 per cent. In addition to gold and silver some copper was won from the deposits. Some of the ores carried up to 0.6 per cent cobalt.

The highly metamorphosed Precambrian Grenville Group in Canada contains a number of lead-zinc deposits carrying both silver and gold. The best known of these are the Tetreault deposit near Quebec City and the New Calumet deposit on Calumet Island in the Ottawa River. The Tetreault deposit produced considerable zinc, lead, gold and silver from orebodies containing abundant skarn minerals, sphalerite, galena, pyrrhotite, pyrite, chalcopyrite, tetrahedrite, stibnite, arsenopyrite, and grading 7 to 10 per cent Zn, 1 to 3 per cent Pb, 0.09 oz Au/ton and 5 to 9 oz Ag/ton (Dresser and Denis, 1949). The New Calumet deposit, now exhausted, was a tabular body of massive and disseminated sulphides in a highly altered impure limestone now essentially composed of pyroxene, tremolite, feldspar, chlorite, garnet and calcite (Dresser and Denis, 1949). The principal sulphides were pyrite, pyrrhotite, sphalerite and galena. The silver content ranged between 5 and 10 oz Ag/ton and there was about 0.05 oz Au/ton. The silver was closely associated with the galena and was present in various silver-bearing minerals, including tetrahedrite, argentite and polybasite. The gold was mainly in the native form associated with all the sulphides and as minute grains in the silicate gangue. One variety of ore, characterized by fine-grained pyrite and pyrrhotite in coarse calcite with feldspar and tremolite, was relatively rich in native gold. This native gold appeared to have been introduced late in the mineralization history of the deposit. It carried minor amounts of silver.

In the Richardson Mine at Eldorado, Ontario, the first gold mine discovered in Ontario (Vennor, 1870), ore was obtained from a skarn zone developed in carbonate rocks near the contact of a granite-syenite stock (Wilson, 1965). The gold occurs in pockets and small seams in skarn composed mainly of diopside, amphibole, epidote, mica, chlorite, talc, coarse calcite, tourmaline and pyrite. In some parts of the deposit brannerite is accompanied by gold, the precious metal being younger, occurring mainly in seams and small fractures in the uraniferous mineral (Steacy *et al.*, 1974*a,b*). In other parts of the deposit the gold occurs in thucholite as finely dispersed particles in a manner such as to suggest exsolution from a hydrocarbon gel (Boyle and Steacy, 1973).

The Richardson Mine is one of many in the eastern Ontario gold belt (Miller and Knight, 1914; Hurst, 1927; Cooke, 1946). Most of these deposits are irregular quartz veins or lodes with considerable amounts of arsenopyrite and pyrite in high grade amphibolites, gneisses and schists. Just north of the Richardson Mine at Bannockburn, auriferous quartz-carbonate veins with much pyrite and small amounts of galena, sphalerite and altaite are present (Rickaby, 1932). The gold occurs in the native form and is also present in small amounts of krennerite.

The ages determined for the deposition of brannerite in the Richardson Mine as given by lead isotopes are as follows: Pb^{206}/U^{238}, 936±28 m.y.; Pb^{207}/U^{237}, 957±29 m.y.; and Pb^{207}/Pb^{206}, 1001±30 m.y. These may be compared with ages carried out on the nearby Deloro stock by Wanless and Loveridge (Rubidum-strontium isochron age studies, Report 1; Geol. Surv. Can. Pap. 72-23). A Rb-Sr wholerock isochron age gave 1059±46 m.y. The K-Ar ages of two riebeckites from the stock gave 875 and 989 m.y.

Gold bearing skarn deposits are common in other parts of the world. Emmons and Calkins (1913) describe a rich gold-bearing contact metamorphic deposit at Cable in Montana. There, granite (granodiorite) contains a block of limestone in which skarn and gold-bearing orebodies are developed. The principal minerals in the ore are calcite, quartz, diopside, actinolite, garnet, biotite, sericite, chlorite, magnetite, specularite, pyrite, pyrrhotite, chalcopyrite, arsenopyrite, and rarely galena and sphalerite. The gold is native, frequently occurring in masses of several pounds. It also occurs finely disseminated in the iron sulphides, in calcite and in quartz. The silver content of the bullion was low.

At Ouray, Colorado, Burbank (1930) mentions gold-bearing contact metamorphic deposits in the Wanakah Mine. The ores include different mineralogical varieties ranging from low-grade ores containing magnetite, garnet and other lime silicates, to massive pyritic ores and galena ores.

Roberts *et al.* (1971) refer to the Battle Mountain (Copper Canyon and Copper Basin) pyrometasomatic deposits in north-central Nevada. The country rocks are silicic and volcanic rocks of the upper plate of the Roberts Mountains thrust (Scott Canyon, Valmy and Harmony formations), which was overlapped by late Paleozoic rocks (Battle Formation, Antler Peak Limestone and the Edna Mountain Formation) and overridden by the Golconda thrust plate. The orebodies at Copper Canyon were mainly in calcareous conglomerate and hornfels of the Battle Formation; adjacent to the Copper Canyon stock these rocks were metamorphosed to calc-hornfels. During late stage metallization processes the silicates were altered to chlorite and clay minerals, and sulphides including pyrite, pyrrhotite, arsenopyrite, chalcopyrite and minor sphalerite and galena were introduced. This ore ranged in grade from 0.5 to 1 per cent Cu, and contained 0.10 to 0.25 oz Au/ton and about 1.5 oz Ag/ton. At Copper Basin, gold ore occurred in metamorphosed limestone beds of the Harmony Formation and in the overlying Battle Formation adjacent to intrusive bodies. This ore contained remnants of garnet, diopside, epidote, pyrite, pyrrhotite and chalcopyrite in a groundmass of chlorite and clay minerals. The copper in the ore occurred mainly as supergene cuprite and chalcocite. The ore mined averaged 2.96 per cent Cu, 0.49 oz Au/ton and 2.15 oz Ag/ton.

In Nicaragua, Central America the Rosita Mine obtained gold-copper ore from a deeply weathered garnet-epidote skarn developed in Cretaceous marbles near a small Tertiary dioritic intrusion (Bevan, 1973). A description of the oxidized and primary orebodies is given in Chapter IV. The La Luz Mine, some 23 mi southwest of the Rosita Mine (Plecash *et al.*, 1963) was somewhat similar. The ore was in silicified epidote-rich skarn and contained much disseminated pyrite, chalcopyrite and fine-grained gold. The average grades were about 0.107 oz Au/ton, 0.032 oz Ag/ton and 0.4 per cent Cu.

In the Soviet Union a number of skarn deposits are mined essentially for gold, particularly in the Altai-Sayan. These have been described in detail by Vakhrushev (1972). The Sinyukhinskoe in the Gorny Altai, the Lebedskoe in the Gornaya Shoriya and the Natal'evskoe deposits in the Kuznetskii Alatau are in Paleozoic limestones, limy shales and argillites, and dolomites intruded by lower Paleozoic intrusions of the granodiorite-diorite clan. The deposits all occur in skarns containing mainly wollastonite, garnet and diopside mineralized with magnetite, bornite, chalcocite, chalcopyrite, arsenopyrite, pyrite, pyrrhotite, galena, tetrahedrite-tennantite, sphalerite, gold, the tellurides, melonite and altaite, and a number of rarer minerals. The quantity of sulphides is low in the deposits, generally less than a few per cent. Native bismuth occurs in the Natal'evskoe deposit. In a similar deposit, the Tardanskoe, in Tuva, U.S.S.R. also described by Vakhrushev, the gold is rich in the magnetite parts of the skarn especially where serpentine and phlogopite are present. In most of the deposits the gold is relatively fine averaging about 930; the gold in the Natal'evskoe deposit is relatively rich in silver. Electrum was also noted in this deposit. Details of the distribution of gold in the Tardanskoe and Natal'evskoe deposits are given by Kudryavteseva (1969) and Vasil'ev (1970) respectively. Other skarn deposits in U.S.S.R. in Kirghizia, Gornyi Altai and elsewhere are described by Andreev *et al.* (1970), Davletov *et al.* (1972) and Shcherbakov *et al.* (1972).

Small deposits of siliceous gold ores with high temperature calc-silicates occur in the Bau mining district, Sarawak, Malaysia (Wolfenden, 1965; Pimm, 1967). The ores occur as irregular pods or lenses along joints and fractures in Upper Jurassic marbles invaded by mid-Miocene acidic porphyry stocks, dykes and sills. The predominant calc-silicate minerals are wollastonite, grossularite, vesuvianite, andradite, diopside, epidote and rarely plagioclase; other gangue minerals include quartz, calcite, pyrite, arsenopyrite, sphalerite, chlorite and apatite. Stibnite is abundant in some of the lenses, in places in commercial quantities. The gold is coarser in some of the lenses, whereas in others it is finely disseminated. The tenor of the ores is about 0.5 oz Au/ton, with richer ores running 1 to 4 oz/ton.

Skarns constitute the most predominant type of mineral deposit in the Suian district of Korea (Watanabe, 1943). Most are found near the contact of the Suian granite. The orebodies are irregular in form, consisting of lime-magnesian-silicate gangue minerals, pyrite, chalcopyrite, pyrrhotite, arsenopyrite, loellingite, bismuthinite, tetradymite, sphalerite, galena, molybdenite and gold. The greater part of the gold and copper production of the Suian mining district has come from orebodies of this type. In some skarn deposits borate minerals, such as kotoite, ludwigite, etc., are abundantly found as gangue minerals. The age of the mineralization is thought to be late Mesozoic.

Gold-silver and silver-gold veins, stockworks, lodes, mineralized pipes and irregular silicified bodies, in fractures, faults, shear zones, sheeted zones and breccia zones essentially in volcanic terranes

Representatives of this type of deposit are widespread throughout the folded and relatively flat-lying volcanic terranes of the earth. The deposits occur in rocks of all ages, but the largest number occur in those of Precambrian and Tertiary age.

The favourable host rocks are commonly basalts, andesites, latites, trachytes and rhyolites. In Precambrian rocks such assemblages are usually referred to as 'greenstones'. Many deposits occur in tuffs, agglomerates and sediments interbedded with the volcanic flows, particularly in banded iron-formations. In the older terranes, the rocks are generally regionally metamorphosed and exhibit the characteristic regional metamorphic facies outward from igneous or granitized centres. The younger rocks generally show the effects of chloritization (propylitization) over broad areas, but locally some of the andesites and rhyolites may be relatively fresh.

In the older rocks the deposits are veins, lodes, stockworks, pipes and irregular mineralized masses generally in extensive fracture and shear zone systems. Some occur in drag folds. The deposits in the younger rocks are usually confined to fissures, fractures, faults and brecciated zones that often have a limited horizontal and vertical extent. Others, however, are associated with fracture and fault systems that extend for many miles.

The structure of the veins and lodes in the older rocks is generally compact, and the minerals are commonly intimately intergrown with one another. Recrystallization and a coarse-grained character are common. Replacement features abound, and book and ribbon structures are common in the quartz of the veins. The structure of the younger, generally Tertiary, deposits is characteristic. Open cavities are abundant, and filling, crustification, and comb and cockade structures are conspicuous. The vein walls are often irregular, and the vein matter is generally frozen to the walls. Banding and repeated surges of mineralization, witnessed by numerous overgrowths, are characteristic.

Quartz is the most important gangue in these deposits. In the older rocks the quartz is colourless, white, milky, grey or black, and forms coarse granular aggregates, intimately intergrown with the other vein minerals. Most of the quartz gives the appearance of being considerably recrystallized, and some varieties have a definite schistose and gneissic appearance. In silicified zones the quartz is usually microcrystalline. Vugs and crusts of quartz crystals occur in some deposits, but they are rare. The quartz in the younger rocks is characteristically white or light grey, and in some deposits an amethyst colour is often noticeable. It is usually fine grained and often chalcedonic. Some varieties exhibit a delicate colloform banding suggesting colloidal deposition. Several generations are often present, and these cement older brecciated quartz aggregates, ore minerals and wall-rock fragments.

Other gangue minerals in the older deposits include calcite, dolomite and ankerite. In the younger deposits, barite and fluorite are also common, and rhodochrosite and rhodonite are characteristic. Adularia is commonly developed in some Tertiary deposits, and kaolinite, dickite and other clay minerals, sometimes in abundant amounts, are present in the veins. Most are of hypogene origin, but some may be a product of descending surface waters. Zeolites occur in a few of the younger deposits.

The metallic minerals are varied and seem, in part, to be dependent on the age of the deposits. Native gold is the most common. In the older deposits it tends to be relatively pure with only a little silver, the ratio of Au/Ag ranging between 5:1 and 50:1. The gold of the younger deposits is usually much richer in silver, the ratio Au/Ag approaching 1:1 or less in some districts. Gold and silver tellurides commonly occur in all ages of deposits, but are particularly abundant in the younger deposits. Both the native gold and gold-silver tellurides tend to be late minerals in the paragenetic sequence of the veins. Silver selenides occur in some of the younger deposits, but these minerals are generally rare.

The principal silver mineral in the deposits is acanthite (argentite). In addition there may be proustite, pyrargyrite, miargyrite, stephanite, polybasite and tetrahedrite-tennantite. Native silver is common, but is often an oxidation product. These silver minerals are rare in the older (Precambrian) deposits; but a little silver-bearing tetrahedrite-tennantite and other silver sulphosalts may occur in some veins. Most of the deposits that are rich in silver minerals are in Paleozoic, Mesozoic or Tertiary rocks.

Among the other metallic minerals, pyrite, arsenopyrite, argentiferous galena, sphalerite and chalcopyrite are ubiquitous in all ages of deposits, although the last three minerals are generally present in only small amounts in the Precambrian deposits. Pyrrhotite occurs in some of the older deposits, but is rare in the younger. Stibnite and a variety of sulphosalts are most common in the younger deposits, but also occur in some abundance in certain Precambrian ones. Alabandite is usually restricted to the younger deposits. Molybdenite and scheelite are present in certain Precambrian deposits but are relatively rare in younger veins, although there are exceptions to this generalization.

Characteristic types of wall-rock alteration are generally developed adjacent to and in the vicinity of nearly all deposits in this class. In the old Precambrian rocks the most common types of alteration are chloritization, carbonatization, sericitization, pyritization, arsenopyritization and silicification. In the younger rocks propylitization (chloritization and pyritization) is especially characteristic, and there may also be a development of adularization, silicification, kaolinization, sericitization and more rarely alunitization.

Veins in Precambrian greenstones and in certain younger andesites and trachytes are generally flanked by zones of carbonate-sericite schist, which grade imperceptibly into zones of chlorite-carbonate and chlorite schist and then into the country rock. In general these alteration zones represent a loss of silica and some of the cafemic elements, and major increases in water, carbon dioxide, sulphur and potassium. Sodium is generally leached. The reactions to produce the alteration zones are complex and have been discussed in the previous section. The most significant feature is the transfer of silica to the vein sites where it probably crystallized as quartz. By means of detailed chemical profiles it can be shown that most of the vein quartz owes its origin to this process.

Where rhyolites or dacites are present the alteration effects are less marked. Sericitization, pyritization and silicification are, however, characteristic. Sediments, interbedded with the volcanic rocks, are not markedly affected in most places, although there may be a development of pyrite, sericite and some carbonate minerals near the veins.

Propylitization is characteristic of many Tertiary and younger deposits. The mineralogical changes include the abundant development of chlorite and pyrite, sometimes also epidote, from the ferromagnesian minerals in andesite and similar rocks. There is also a development of carbonates and some sericite in certain areas. The chemical changes consist of a moderate leaching of potassium and sodium, a decrease of silica and cafemic elements, and additions of water, sulphur and carbon dioxide in some areas. The propylitization is pervasive, being developed usually adjacent to the veins as well as in great volumes of rock in the general vicinity of the mineralized zones.

The alteration in the younger rhyolites and dacites is usually sericitization and silicification. Alunitization, the development of adularia and carbonatization may affect all younger rock types. Silicification, without the development of lime silicates, may take place in limestones and limy shales. Sandstones, shales and argillites are generally little altered.

The Precambrian deposits of this class exhibit remarkably little vertical elemental zonation; the younger deposits, on the other hand, especially those of Tertiary age are commonly markedly vertically zoned. From the surface downward the sequence is frequently Au-Ag, Pb-Zn, Cu. With greater depth the copper zone tends to pass into barren zones of quartz, carbonates and pyrite with only scattered base metal sulphides. In some Tertiary deposits there is a marked decrease and often an abrupt cessation of silver sulphosalts with depth. Tellurides may also exhibit this effect in some deposits. Increase in the contents of pyrite and the sulphides of Pb, Zn and Cu are common. At great depth the Precambrian deposits commonly pass into barren quartz and carbonates with scattered pyrite, pyrrhotite and minor base metal sulphides, although in some cases the structures appear to fail and mineralized rock no longer occurs. Pyrrhotite takes the place of pyrite at depth in some of the gold belts of the Canadian Shield, and there is commonly a decrease in the stibnite and sulphosalt content of the ores with increasing depth. In these belts, however, the gold and silver values are usually maintained at or near the amounts encountered near the surface.

Some deposits exhibit an increase in the Au/Ag ratio with depth (*see also* the section on Au/Ag ratios in this chapter). In some belts e.g., Kolar, India, there is apparently little diminution in gold values to depths as great as 10 200 ft, but the fineness of the gold is said to increase with depth, from 800 in the near-surface parts to 900 at depth.

The elements commonly concentrated in this class of deposits include Cu, Ag, Zn, Cd, Hg, B, Tl, Pb, As, Sb, Bi, V, Se, Te, S, Mo, W, Mn, Fe, (Co), (Ni), CO_2 and SiO_2; less commonly Ba, Sr, U, Th, Sn, Cr and F. Hg and Sb are particularly characteristic of the younger deposits. The source of these elements is probably the volcanic pile within which the deposits are enclosed. Interbedded sediments may also have made a major contribution of elements to some of the deposits. Tertiary gold-silver and silver-gold base metal deposits in relatively flat-lying volcanics such as andesites and dacites may have derived many of their elements from underlying older rocks in the basement. This and other speculations on the origin of the Tertiary deposits are discussed in a subsequent section on the origin of gold deposits.

Numerous deposits belong in this category. At least two general types can be recognized – one characterized by the presence of native gold as the principal economic mineral and the other by the presence of economic amounts of gold tellurides and/or native gold with or without selenides. Short descriptions and examples of these two general types follow.

Gold-silver and silver-gold deposits

Native gold, alloyed with variable though generally small amounts of silver, is the principal economic mineral in the gold-silver type. In some deposits gold-silver tellurides and aurostibite may contribute to the economic value of the deposits. The Au/Ag ratio of the deposits is 1 or more, in some deposits as high as 12 or more. Quartz is the principal gangue usually with subordinate amounts of carbonates. Other characteristic minerals include pyrite, pyrrhotite, arsenopyrite, chalcopyrite, and minor galena and sphalerite. Small amounts of silver minerals such as acanthite (argentite), tetrahedrite-tennantite, pyrargyrite, proustite, etc. occur in some deposits, usually younger than Precambrian.

The silver-gold deposits contain native gold (commonly electrum), gold-silver tellurides and a veritable host of silver minerals as the economic minerals. The principal primary silver-bearing minerals are tetrahedrite-tennantite, acanthite (argentite), pyrargyrite, proustite, pearceite, stromeyerite, naumannite, miargyrite and matildite. The Au/Ag ratio of the deposits is invariably much less than 1.

Deposits of the gold-silver and silver-gold types range in age from Precambrian to Tertiary. Most are of Precambrian, Paleozoic and Tertiary age.

Numerous examples occur in the greenstone belts of the Canadian Precambrian Shield, including those in the following districts: Yellowknife, Northwest Territories; Rice Lake, Manitoba; Crow River, Lake of the Woods, Red Lake, Porcupine and Kirkland Lake, Ontario; and Belleterre, Noranda-Rouyn, Val d'Or and Chibougamau, in western Quebec.

The deposits of this type at Yellowknife (Boyle, 1961*a*; Henderson and Brown, 1966) are lenses, veins, stockworks and silicified zones in extensive chlorite schist shear zones that intersect meta-andesites, basalts and dacites with interbedded pyritiferous slates and tuffs (Fig. 17). These rocks are cut by quartz-feldspar porphyries in places and by granodiorite along their western limit. The deposits are younger than both the quartz-feldspar porphyries and granodiorite. The alteration of the volcanic rocks includes chloritization, carbonatization, arsenopyritization, pyritization and sericitization, the last four especially intensive near the quartz bodies and silicified zones (Fig. 18). The principal minerals in the quartz deposits are ankerite, pyrite, arsenopyrite, stibnite, chalcopyrite, sphalerite, galena, tetrahedrite, a number of other Pb, Cu and Fe sulphosalts, tellurides in places, molybdenite and scheelite. The economic minerals are native gold and aurostibite. The sulphides and sulphosalts carry considerable amounts of gold in a finely divided form. The grade of the ores ranges from 0.5 to 1 oz Au/ton or more. The Au/Ag ratio of most ore shoots ranges from 3 to 6, but in some orebodies, especially where silver minerals such as tetrahedrite are common, the ratio is 0.7 to 0.9.

The San Antonio Mine in the Rice Lake district of Manitoba is within a sill of diabase that lies in tuff, arkose and conglomerate of the Rice Lake Group. (Gibson and Stockwell, 1948; Stephenson, 1971). The deposit consists of en echelon quartz veins and lenses flanked by zones marked by chloritization, carbonatization, pyritization and sericitization (Fig. 19). The principal minerals are ankerite, chlorite, tourmaline, pyrite, arsenopyrite, sphalerite, galena, chalcopyrite, pyrrhotite, magnetite, petzite and tellurobismuth. The grade of the ore is about 0.35 oz Au/ton.

Numerous gold-quartz veins and lodes occur in the highly metamorphosed greenstone belts and gneisses intruded by granitic rocks between Thunder Bay and the Manitoba border (Cooke and Johnston, 1932; Bruce, 1933; Thomson, 1936; Beard and Garratt, 1976). Most are concentrated in the Lake of the Woods area where mining and exploration were extensive at the turn of the century. The deposits, now exhausted, produced about 100 000 oz of gold from four principal mines, the Mikado, Regina, Sultana and Laurentian. The orebodies were mainly quartz veins, quartz stockworks and silicified zones in shear zones and fractures in amphibolites (greenstones), gneiss, schist, felsic intrusives and extrusives and granitic rocks. The mineralization was essentially quartz with ankerite and small amounts of pyrite, arsenopyrite, chalcopyrite, bismuthinite, molybdenite, free gold and minor tellurides. Tourmaline was common in some of the veins. The gold was coarse in many of the veins, especially near the surface, and the grade exceeded 1 oz/ton in many cases. Grade decreased markedly at depth, however, and few veins were economic below 750 ft. Opportunities for further discoveries of economic deposits in the region seem good.

The gold ore deposits of the Red Lake area, northwestern Ontario are varied (Horwood, 1945). Some occur in granodiorite (Red Lake Gold Shore); others are disseminations in quartz-feldspar porphyry (Howey-Hasaga) or in tuffs (Madsen). A number of deposits occur in shear zones, fractures and faults in meta-andesites, basalts and tuffs (greenstones). The Cochenour Willans Mine (Kuryliw, 1957) is in a volcanic sequence ranging from rhyolite to andesite, now highly altered as a result of chloritization, carbonatization, albitization, silicification and pyritization. The orebodies are quartz and quartz-carbonate lenses in shears and fractures of considerable

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extent, mainly in tuffs and altered volcanic rocks. The mineralization is primarily quartz and ankerite with free gold. Associated minerals are pyrite, arsenopyrite, sphalerite, pyrrhotite, chalcopyrite, stibnite and tellurides.

The Central Patricia Mine in the Crow River district of Ontario is in the greenstone belt north of Lake St. Joseph (Barrett and Johnston, 1948). The gold deposits are quartz veins and sulphide stringers mainly in fractures in banded iron-formation (Fig. 20). The principal minerals are pyrrhotite, arsenopyrite, green chlorite and ankerite. The gold is mainly free and averages about 0.33 oz/ton in the orebodies. At the Pickle Crow Mine (Bothwell, 1938; Corking, 1948) in the same district ore was mined from one quartz vein (Howell vein) mainly in iron-formation and another quartz vein in sericitic quartz porphyry. There are also veins in greenstones (Fig. 21). The principal minerals are pyrite, chalcopyrite, pyrrhotite, arsenopyrite, tourmaline and chlorite. The average grade of the ore was 0.6 oz Au/ton and 0.05 oz Ag/ton; the Au/Ag ratio was 12.

The deposits of the Porcupine (Timmins) district, Ontario, (Dunbar, 1948; Goodwin, 1965*a*; Ferguson, 1966; Davies, 1977) are mainly extensive quartz veins, silicified zones and silicified, sericitized and pyritized zones in sheared, fractured and highly altered (carbonatized and chloritized) Keewatin lavas and pyroclastics that range in composition from rhyolite to andesite. Some quartz veins, stockworks, silicified zones and pyritized zones produce much gold from quartz-feldspar porphyry and Temiskaming-type sediments. The vein systems are extremely complex as shown by the plans of the Hollinger orebodies (Fig. 22) and the descriptions of Ringsleben (1935), Buffam (1948*a,b*), Jones (1948*a*), Furse (1948), Carter (1948), Taylor (1948), Kinkel (1948), Longley and Lazier, (1948), Hawley and Hart, (1948), Holmes (1948), Bell (1948), Backman (1948), Price and Bray (1948), Byers (1948) and Griffis (1962). The age of the mineralization at the Preston East Dome Mine as calculated from lead isotope data on galena closely associated with gold is given as 2961 m.y. (Machairas, 1970*a*). The alteration is essentially chloritization, carbonization, sericitization, silicification and pyritization. The principal minerals are quartz, ankerite, calcite, tourmaline, anhydrite, pyrite, pyrrhotite, galena, sphalerite, chalcopyrite, arsenopyrite, native gold, tellurides and scheelite. The grade of the ore ranges from 0.1 to 0.4 oz Au/ton; the silver content ranges from 0.03 to 0.07 oz/ton; and the Au/Ag ratio averages about 5.5 with some mines having ratios as high as 10 or more, especially from near surface veins. Some parts of the deposits contained considerable amounts of tungsten. The Hollinger veins in places averaged about 0.33% WO_3, all in scheelite.

Many of the gold deposits of the Kirkland Lake–Larder Lake district (Thomson, 1950; Thomson *et al.*, 1950) are in rocks other than volcanics and are described in a later section. Some of the deposits in the eastern part of the district, particularly the Kerr Addison Mine and Chesterville Mine are in highly sheared, altered and mineralized volcanics and tuffs ranging in composition from dacite to andesite. The orebodies

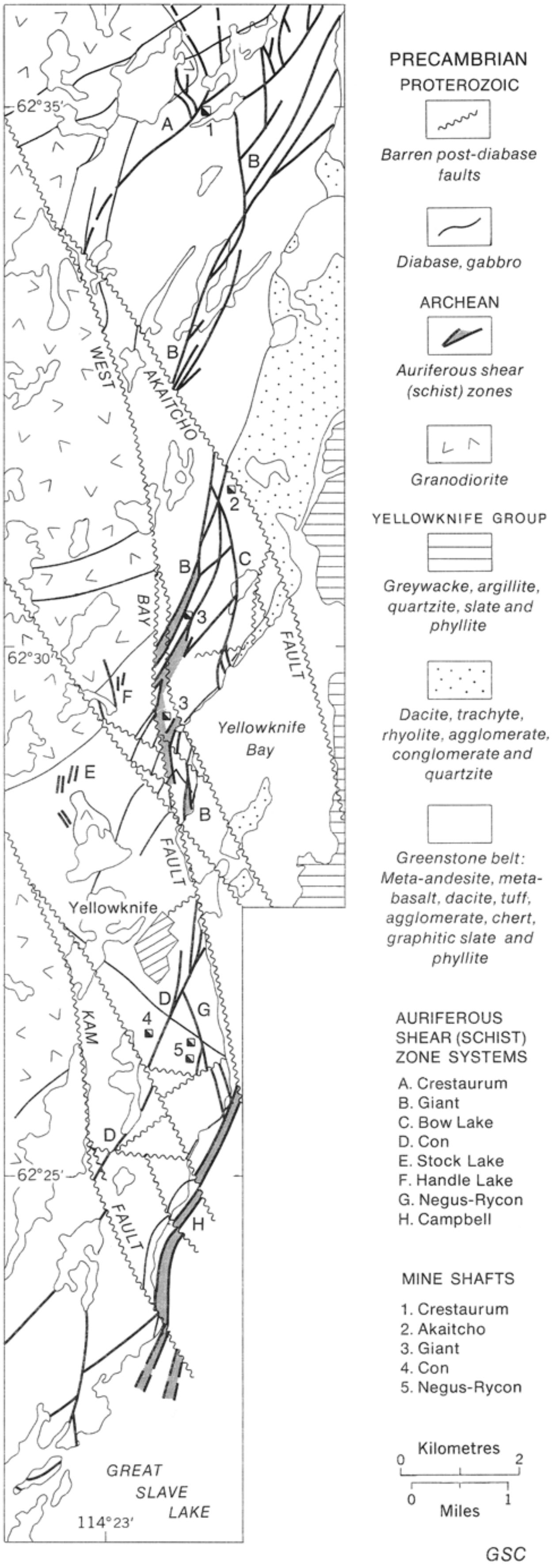

Figure 17. Yellowknife Greenstone Belt showing principal auriferous shear zone systems (after Boyle, 1961*a*).

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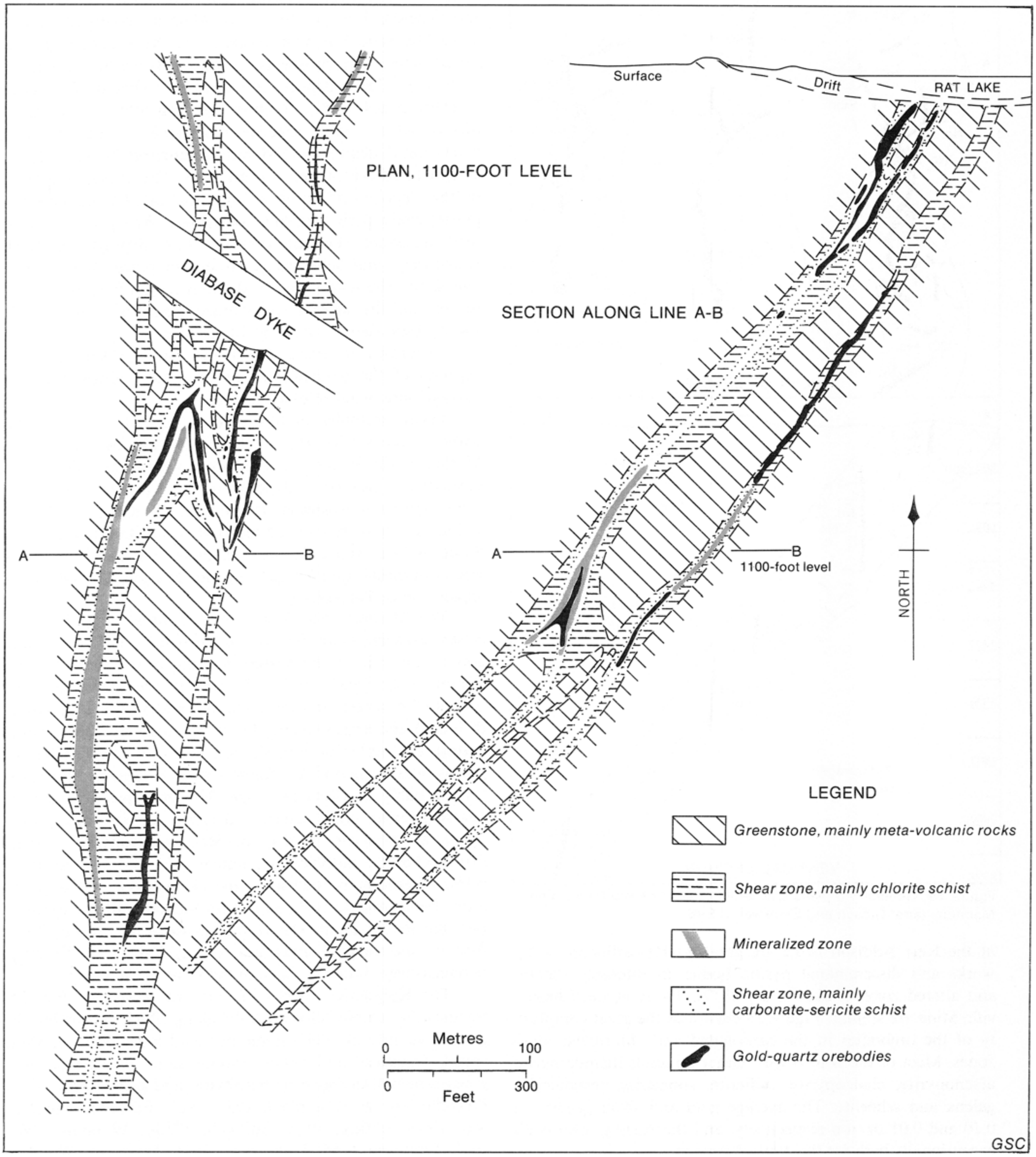

Figure 18. Generalized plan and section of the Con Mine (Con shear zone system), Yellowknife, Northwest Territories (after Boyle, 1961*a*).

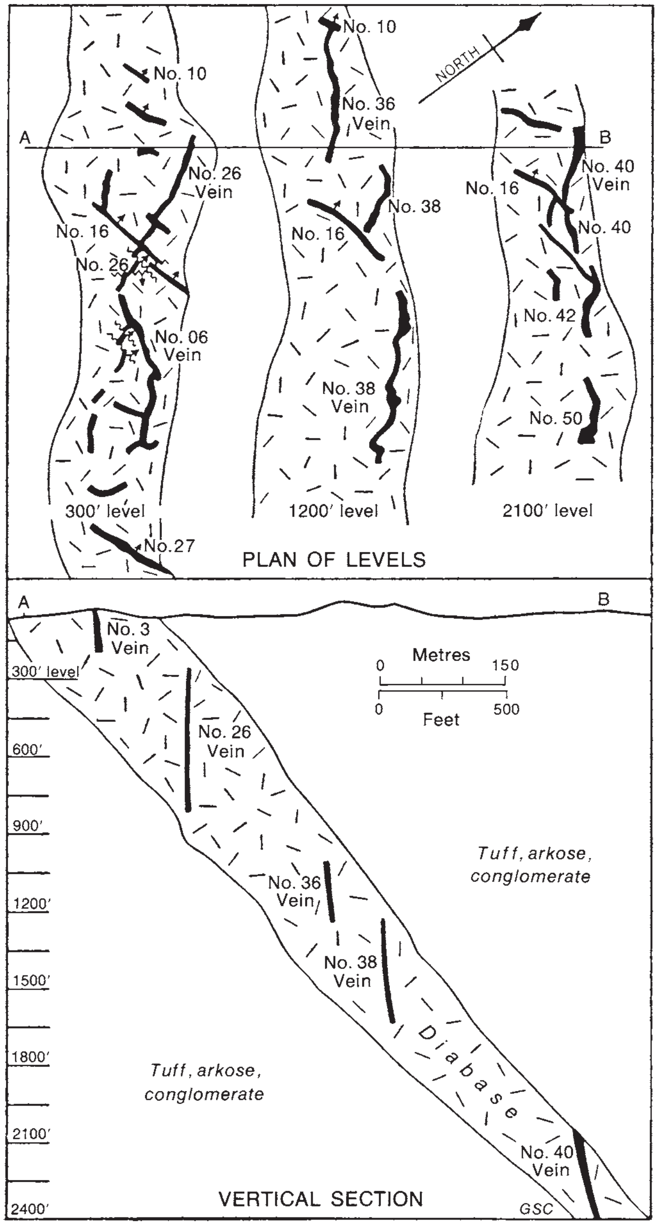

Figure 19. Generalized plans and section, San Antonio Mine, Bissett, Manitoba (after Gibson and Stockwell, 1948).

at the Kerr Addison Mine are great quartz-carbonate stockworks and disseminated pyritic bodies in intensely sheared and altered zones (Baker *et al.,* 1957). Those at the Chesterville Mine are similar. Figure 23 illustrates the great complexity of the orebodies in the carbonated and chloritized schist zones. Most of the gold is free. Other minerals include pyrite, arsenopyrite, chalcopyrite, millerite, sphalerite, tetrahedrite, galena and scheelite. The average gold and silver grades are 0.20 and 0.01 oz/ton respectively, and the Au/Ag ratio is 20, exceptionally high for this type of deposit.

Many of the deposits in the greenstone belts of northwestern Quebec occur in altered volcanics ranging in composition from rhyolite to basalt (Wilson, 1948; Norman, 1948*a, b*; Dresser and Denis, 1949; Dugas, 1966; Latulippe, 1966; Prochnau, 1971). Those in the intermediate and basic varieties of volcanic rocks include among others the Belleterre Mine in Guillet Township; the Francoeur, Arntfield, Wasa Lake, Senator Rouyn and Stadacona in the Noranda-Rouyn district; the O'Brien, East Malartic and Malartic goldfields, in the Lake Malarctic–Val d'Or district; and the Agnico-Eagle and other mines and prospects in Joutel Township, Harricana River area. These deposits are essentially similar. They occur in shear zones, faults, fractures or drag folds and comprise quartz veins, quartz-ankerite replacement zones, silicified zones and disseminated and massive sulphide bodies in highly silicified and carbonated volcanic rock. The principal minerals in the deposits are quartz, ankerite, calcite, arsenopyrite, pyrite, chalcopyrite, galena, tourmaline, free gold and gold-silver tellurides. Hematite occurs in some deposits (Arntfield, Francoeur), and scheelite is present in places but is rarely abundant. The gold grade of the ores ranges from 0.15 to 0.5 oz/ton and the silver grade averages about 0.05 oz/ton. The Au/Ag ratio ranges from 3 to 10 or more.

According to Price (1934) and Dugas (1966) the gold deposits of the Rouyn-Noranda area are younger than the massive base metal sulphide bodies.

Many examples of this type of deposit occur in other parts of the world. Here belong the gold deposits of the Mother Lode System of California where the ores are in greenstones; numerous deposits in the Kalgoorlie and adjacent districts of Australia; the ores of the Kolar goldfield in India; and gold deposits of the Barberton Mountain Land of South Africa. Many Tertiary examples are known in Roumania (Transylvania), New Zealand, Mexico, United States, Japan, Fiji and elsewhere.

The Mother Lode System of California (Fig. 24) comprises two-score mines or more in a belt some 120 mi long and about 1 mi wide on the western foothills of the Sierra Nevada (Knopf, 1929; Clark, 1970). The deposits are quartz veins and bodies of pyritized and mineralized country rock in a system of linked and anastomosing faults, fractures and shear zones cutting a complex of Jurassic and Paleozoic (Carboniferous) greenstones, serpentinites, slates, schists and granodiorite, the last probably of Cretaceous age. The principal minerals are coarse-grained milky quartz, ankerite, calcite, mariposite, pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, tetrahedrite, scheelite, molybdenite, native gold and various tellurides. Alteration is intense in the greenstones and serpentinites, being mainly carbonatization (ankeritization), pyritization and sericitization. The average grade of the ore was 0.3 oz Au/ton, and the gold-silver ratio averaged about 10. Fabulous bonanzas were found in some of the veins of the system.

The Kalgoorlie district of Western Australia (Fig. 25) features the famous 'Golden Mile' along which and within the general vicinity of which numerous gold lodes occur in shear zones, fractures and pipes (intersections of shears) in a greenstone belt intruded by porphyries and granodiorite, all of Precambrian age (Campbell, 1953, 1965; Finucane and Jenson, 1953; Utting, 1953; Stillwell, 1953*a*; Woodall, 1965, 1975; Finucane, 1965; Travis *et al.,* 1971; Travis and Woodall, 1975; Tomich, 1974, 1976).

Two types of orebodies are present: (1) gold and gold telluride mineralization in the lodes of the Golden Mile zone localized mainly within a sill (Golden Mile Dolerite). These are the most productive and comprise steeply-dipping pyritic

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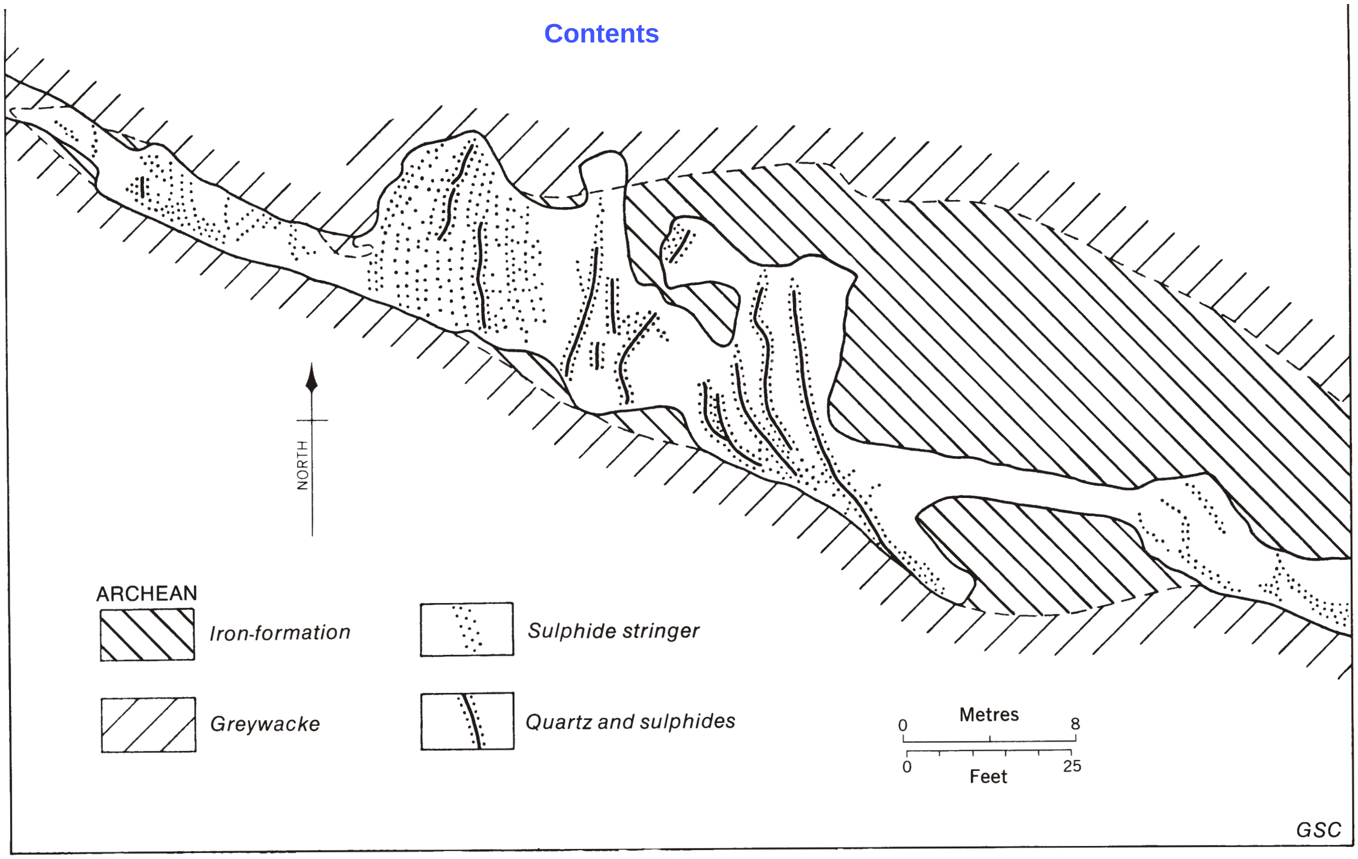

Figure 20. Plan of F-10-3 orebody, 1000-foot level, Central Patricia Mine, Crow River district, Ontario (after Barrett and Johnston, 1948).

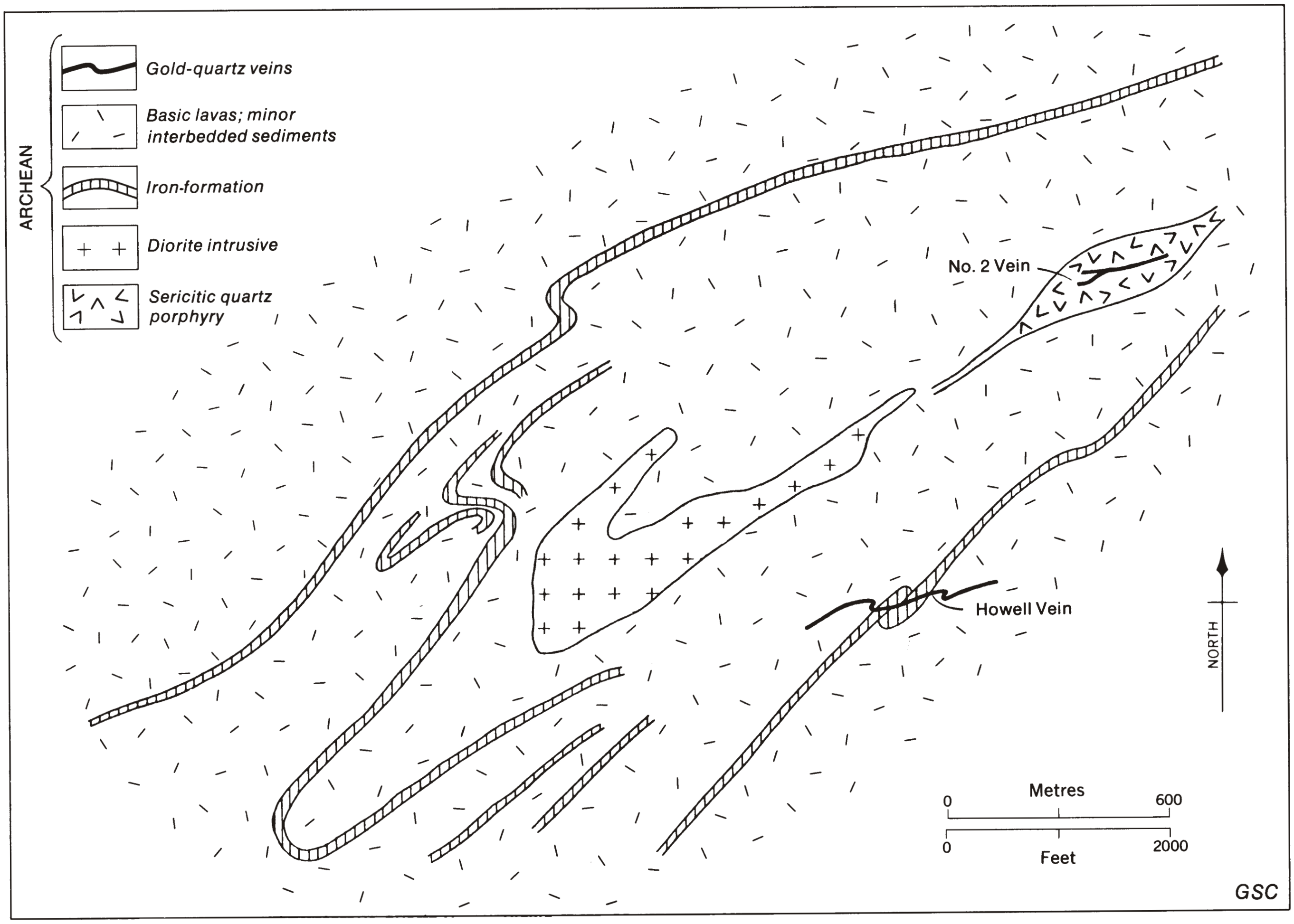

Figure 21. Major structure and auriferous quartz veins, Pickle Crow Mine, Crow River district, Ontario (after Corking, 1948).

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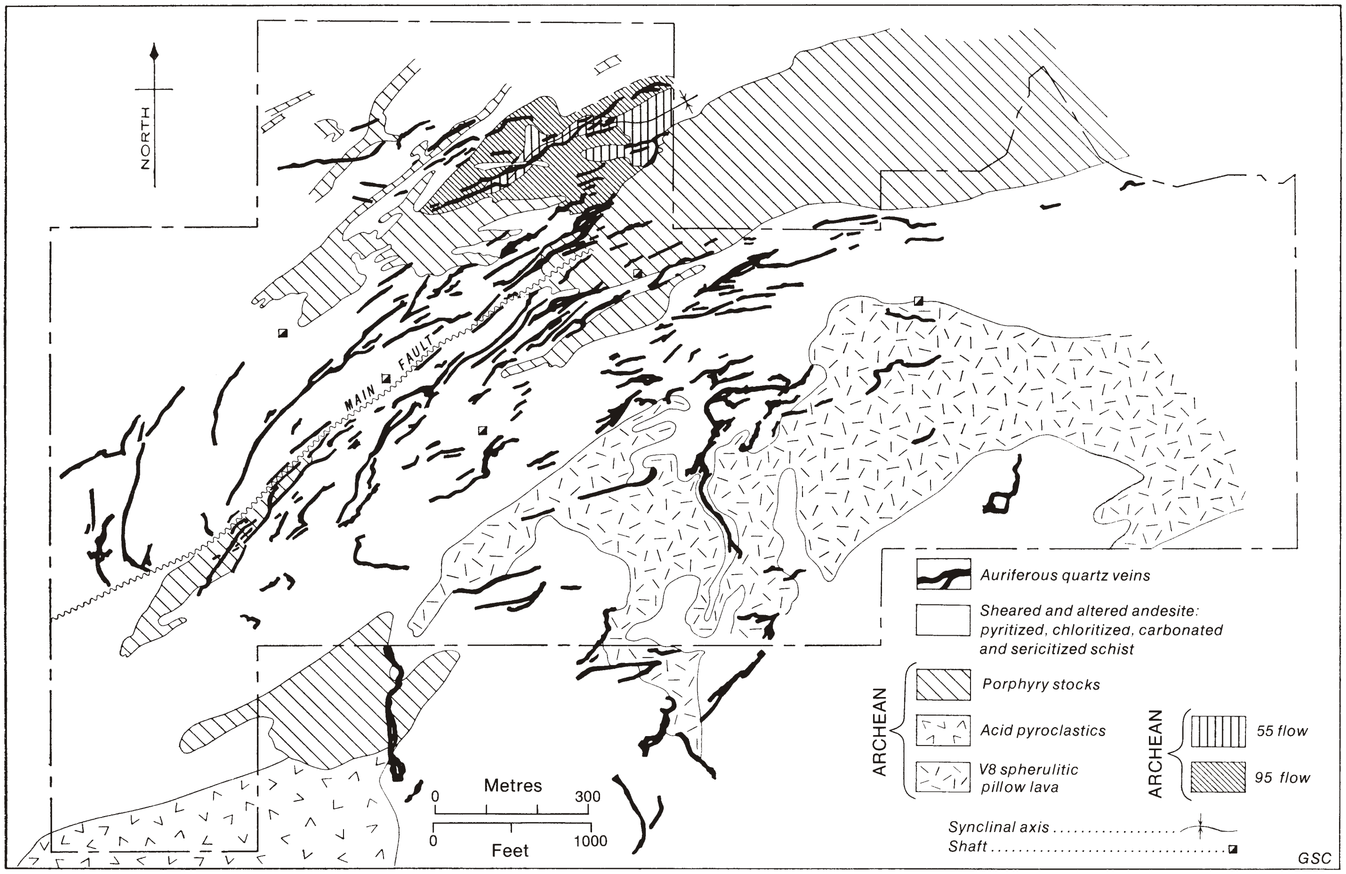

Figure 22. Plan of 425-foot level, Hollinger Mine, Timmins, Ontario, showing complex vein systems

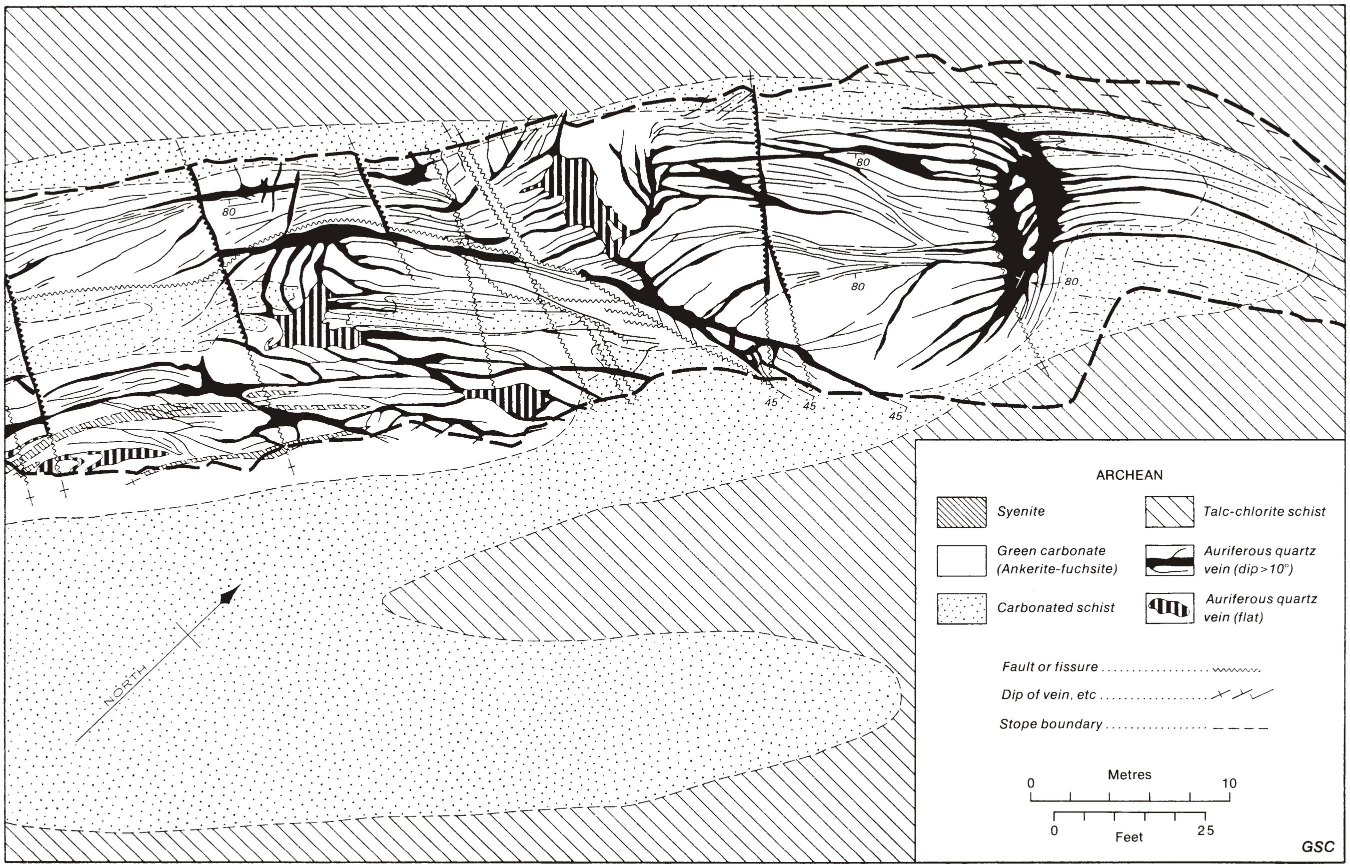

Figure 23. Geological plan of part of the back of a stope, 9th level, Chesterville Mine, Larder Lake, Ontario, illustrating the great complexity of the quartz bodies in the chloritized and carbonated schist zones (modified from Buffam and Allen, 1948).

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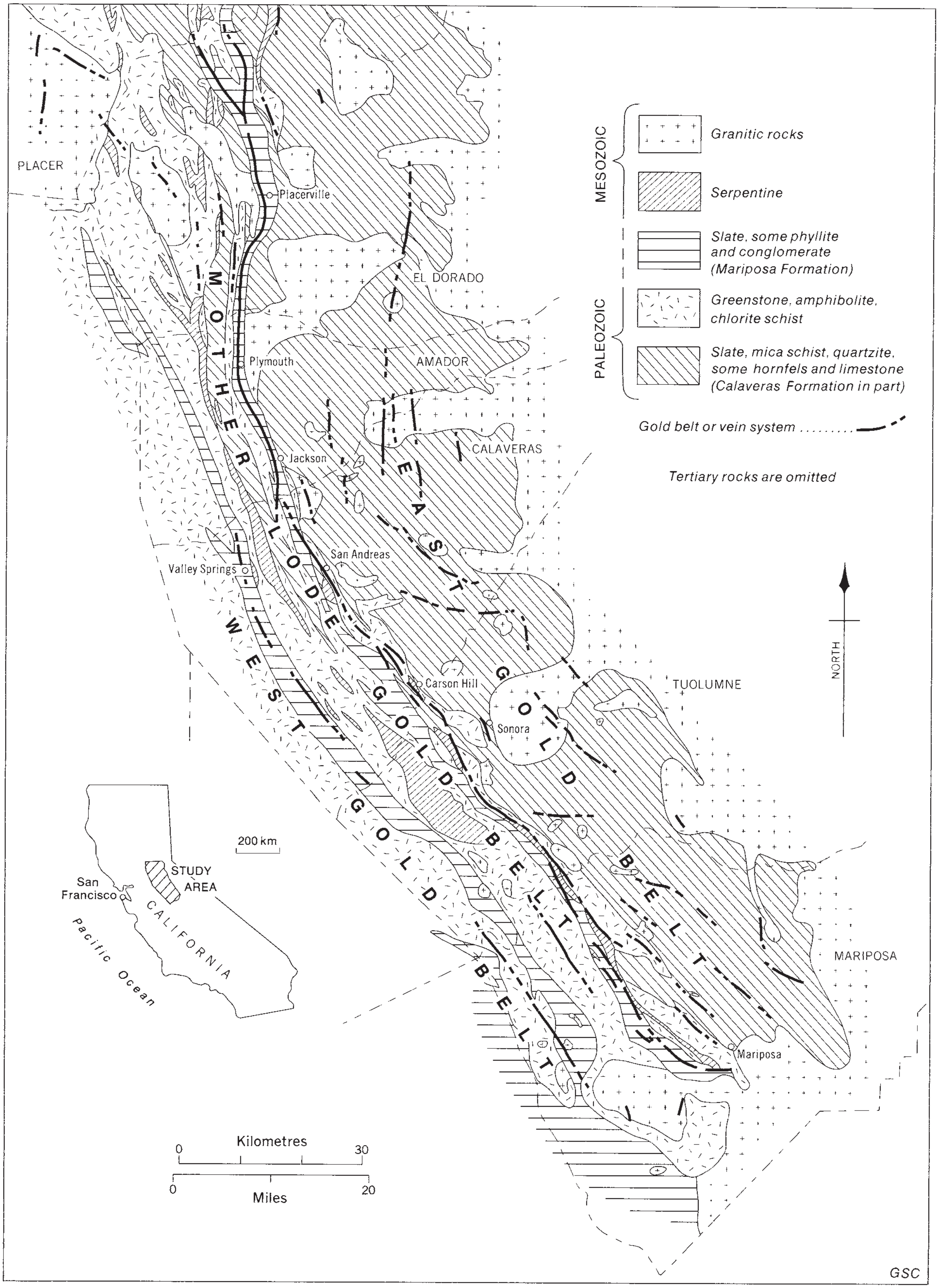

Figure 24. The 'Mother Lode System', Central Sierra Nevada, California. Also shown are the East and West gold belts (after Clark, 1970).

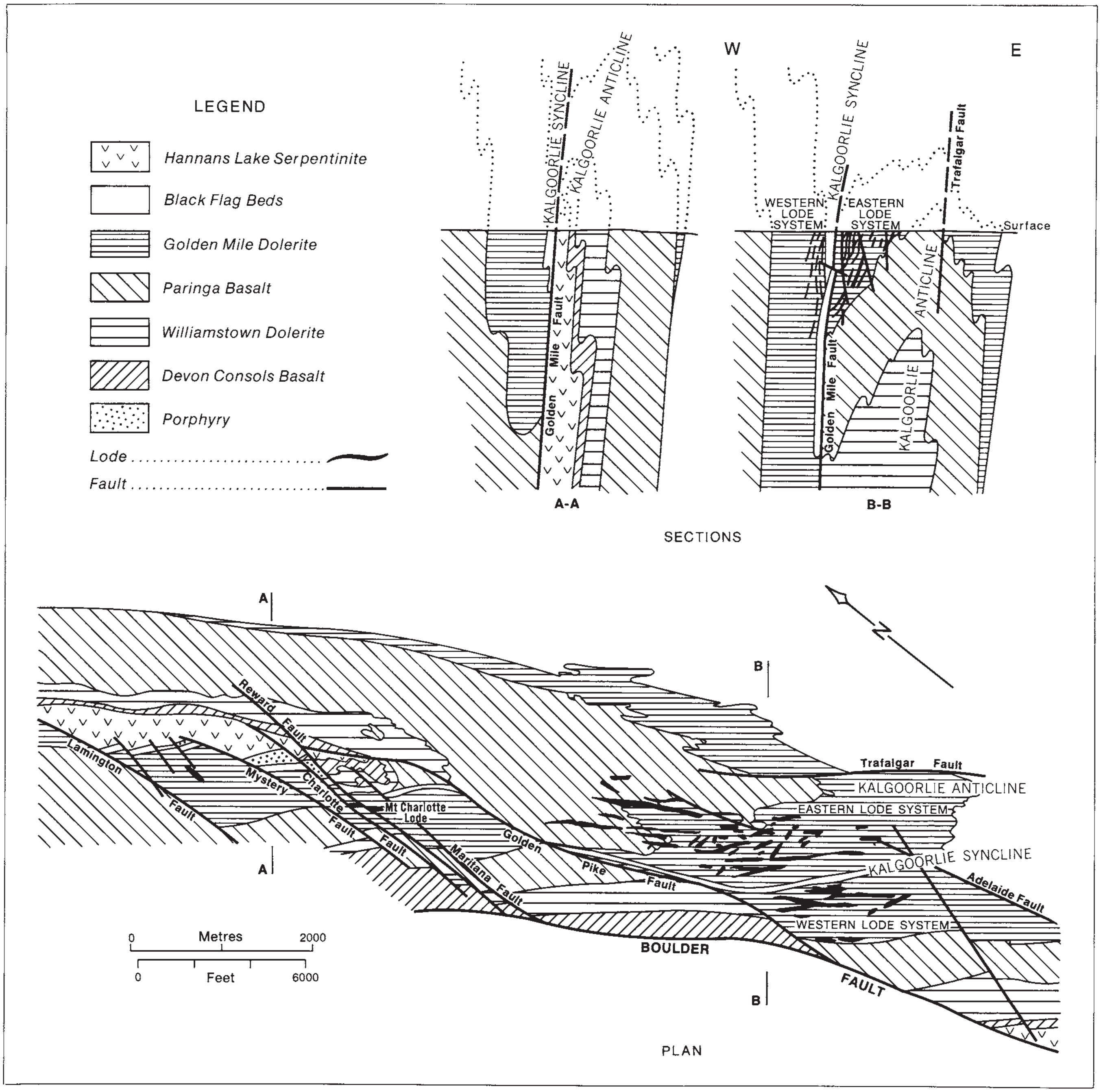

Figure 25. Principal geological features (plan and sections), Kalgoorlie productive area, Western Australia (after Travis *et al.*, 1971).

and silicified replacement bodies along narrow shears and fractures, and (2) gold-quartz mineralization that occurs as replacement bodies along shears or as stockworks of quartz veins (Mount Charlotte Mine). Tellurides are rare in this type of deposit. The principal minerals in the deposits are quartz, ankerite, calcite and pyrite, with small amounts of chalcopyrite, galena, sphalerite, tetrahedrite, stibnite, enargite, pyrargyrite, loellingite, specularite, magnetite, fluorite, tourmaline, native gold and several tellurides. Alteration effects are marked in the greenstones and include chloritization, carbonatization, pyritization and sericitization. The grade of the ore averages about 0.4 oz Au/ton and the Au/Ag ratio is about 8. Deposits somewhat similar to those at Kalgoorlie occur in the Coolgardie greenstone belt (McMath *et al.,* 1953) and in the other greenstone belts of Western Australia and Northern Territory (Hills, 1953; Woodall, *in* Knight, 1975).

The Kolar goldfield of India, worked in a primitive way for centuries and in modern times since 1880, is localized in a sliver of Precambrian Dharwar metavolcanics some 50 mi long and 2 to 3 mi wide in the eastern part of the Mysore Plateau, India. The most recent description of this famous goldfield is by Narayanaswami *et al.* (1960). Other similar fields are in narrow greenstone belts to the northwest at Ramajiri and Hutti (Murthy, 1964; Ghosh *et al.,* 1970). Sikka *et al.* (1964) have discussed the setting of the Kolar and other goldfields in the Precambrian terranes of India and compared the deposits with those of the Porcupine (Timmins) area of Ontario.

The deposits of the Kolar field are quartz lodes and quartz-sulphide bodies in north-striking subparallel schist zones in amphibolites (metavolcanics; greenstones) that can be traced for many miles along their strike (Fig. 26). Some also have great dip dimensions, a few of the lodes being mined down to vertical depths of 10 000 ft or more. The eastern part of the Kolar field is marked by the Muscoom, the famous Champion and Mundy's quartz lodes; in the central and western parts of the field sulphide-bearing lodes that are in places graphitic predominate. Most of these subparallel lodes follow the general strike of the greenstones and exhibit a stratigraphic control. The quartz lodes occur as en echelon bodies within well marked schistose zones. They contain essentially quartz, calcite, native gold, with minor amounts of magnetite, ilmenite, galena, pyrrhotite, pyrite, arsenopyrite, chalcopyrite, tourmaline and scheelite, often mixed with pyroxene, hornblende, cummingtonite, tremolite, epidote, biotite, garnet, wollastonite, dumortierite and minor chlorite. Gold tellurides are mentioned as being present by Rozhkov (1966). The quartz sulphide lodes are similar except that they contain more sulphides (about 10%) including pyrrhotite, arsenopyrite, pyrite, chalcopyrite and minor galena. Both the quartz and sulphide lodes are enveloped by a zone of micaceous schist representing alteration of the greenstones. The schist consists of alternating layers of brown biotite and granular quartz together with minor layers of dark fibrous cummingtonite. Adjacent to individual quartz veins and stringers there is a successive alteration sequence as follows: (1) a thin casing of pale-green diopside at the immediate contact of the vein quartz, followed outward by (2) thick or thin layers of dark hornblende and admixed epidote, and finally by (3) a thick layer of brown mica. Where the lode is composed of numerous parallel veins and stringers of quartz, there are symmetrically alternating layers of quartz, diopside, hornblende-epidote and brown mica. These layers are in places highly drag folded, contorted and sheared as a result of postmineralization shearing or probably premineralization drag folding of highly sheared and fractured wall rock. Streaky layers and lenses of diopside, hornblende, epidote and micaceous material are also seen at places in the highly sheared quartz, which is commonly dark gray to black at these localities.

The gold content of the Kolar lodes varies widely but averages about 0.4 oz/ton in the quartz lodes and 0.3 in the sulphide bodies; the Au/Ag ratio ranges from 8 to 10.

The Hutti gold deposits, Raichur district, Mysore are similar to those in the Kolar gold belt. They lie in the broadest part of the Precambrian Hutti-Maski schist (greenstone) belt (Dharwars). According to Vasudev and Naganna (1973) the deposits are mainly gold-quartz veins and lenses in narrow shear zones in basic metavolcanic rocks (amphibolites to chlorite schists) intruded by granites and aplites. Six reefs are productive; these contain quartz, chlorite, biotite, sericite, actinolite, hornblende, tourmaline, calcite, siderite and ankerite as gangue minerals in which are found native gold, pyrite, arsenopyrite, pyrrhotite, chalcopyrite, sphalerite, galena, specularite, rutile and ilmenite. No tellurides are present. Vasudev and Naganna (1973) recognized three distinct stages in the mineralization history of the deposits. Minerals formed during the first stage were rutile (residual in wall rocks), pyrite (with traces of gold), arsenopyrite, specularite, quartz and carbonate. Minerals of the second stage were pyrrhotite, chalcopyrite, sphalerite, galena and gold. Minerals of the third stage were pyrite, calcite and quartz developed along numerous minor faults (slips) and major faults. Based on textural characteristics and associations, three generations of gold can be distinguished as follows: (1) gold-pyrite association; (2) gold-arsenopyrite-quartz association; and (3) gold-sphalerite-quartz association. Only the gold of the second and third generations are important in the economics of the deposits.

The Barberton Mountain Land of South Africa, some 175 mi east of Pretoria, represents an ancient Precambrian (Swaziland System) greenstone belt, composed of a basal volcanic assemblage overlain by sedimentary successions and invaded by granitic rocks (De Villiers, 1957; Davies and Hunter, 1964; Gribnitz, 1964; Anhaeusser *et al.,* 1968; Viljoen *et al.,* 1969; Anhaeusser, 1976). The gold deposits, comprising quartz veins and lenses in greenstones, sediments and granodiorite, pyritic ores in fractured cherts and other sediments, and complex sulphide ores in porphyry, are localized in faults, fractures and shears. Some of the deposits in the Steynsdorp goldfield show a well-defined stratigraphic control. The most abundant minerals in the deposits are quartz, siderite, ankerite, calcite, pyrite, arsenopyrite, pyrrhotite, chalcopyrite, sphalerite, galena, stibnite, tetrahedrite, berthierite, bournonite, argentite, pyrargyrite, millerite, linnaeite, skutterudite, cobaltite, native bismuth and native gold. A number of other sulphosalts and sulphides are mentioned by De Villiers (1957). The Au/Ag ratio of the deposits is high, averaging about 33.

Somewhat similar desposits are present in the Murchison Range of the Northeastern Transvaal, some 200 mi northeast of Pretoria (Hall, 1930; Van Eeden *et al.,* 1939; Sahli, 1961). There, the Swaziland System comprises greenstone and other

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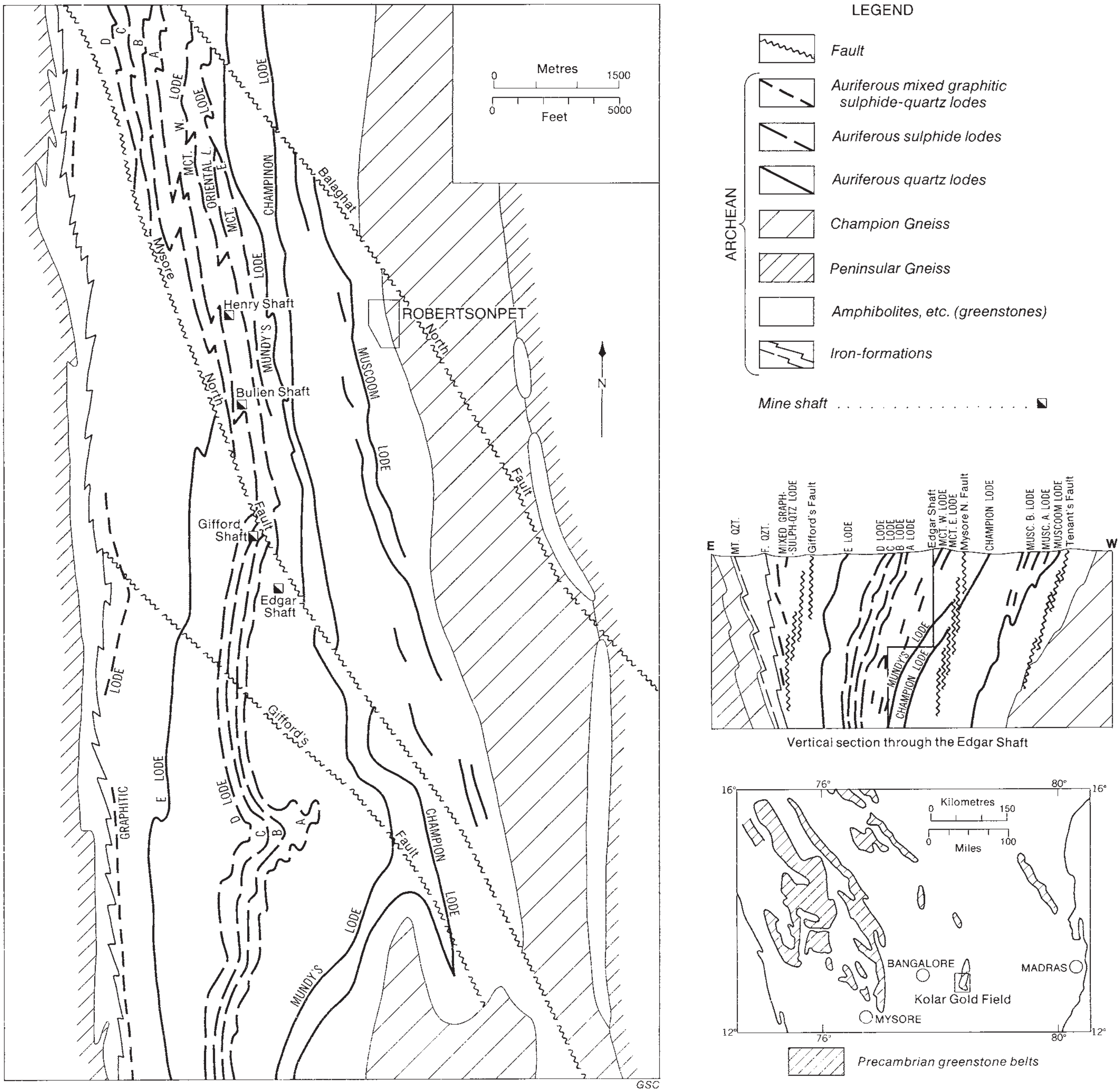

Figure 26. Generalized plan and section of the Kolar goldfield, Mysore, India (modified from Narayanaswami *et al.*, 1960).

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schists invaded and surrounded by granitic rocks. The deposits are mainly quartz veins, sheeted zones and mineralized silicified zones in faults, fractures and shears along a prominent break (The Antimony Line). The deposits carry quartz, pyrite, carbonates, tetrahedrite, chalcopyrite and free gold. Stibnite is abundant in some of the deposits; these produce both gold and antimony. Some deposits also carry cinnabar as a very late mineral.

Northward in the African Shield gold deposits in or closely associated with ancient volcanic rocks have been mined extensively in Rhodesia (Lightfoot, 1930; Phaup, 1964; Goldberg, 1964; Visser, 1968; Anhaeusser, 1976), Zaire (Woodtli, 1961*a, b*), and in Sudan and Egypt (El Boushi, 1972; Neubauer, 1962).

Lightfoot (1930) classified the gold deposits of Rhodesia into five categories: (1) pyritic impregnations along shatter belts; (2) antimonial (stibnite) impregnations along shatter belts; (3) pyritic gold-quartz veins; (4) antimonial (stibnite) gold-quartz veins; and (5) cupriferous gold-quartz veins, containing mainly gold, auriferous pyrite and chalcopyrite. Greenstone schist is said to be the most kindly rock, followed by iron-formation, dolomitic schist, quartzites and granite.

The Cam and Motor Mine (Collender, 1964), the largest gold producer in Rhodesia, wins gold from quartz veins and quartz stockworks in lavas (greenstones), along lava-sediment contacts and in beds of sediments interbedded with lavas. The mineralization is characterized by the presence of ankerite, pyrite, arsenopyrite, stibnite, sphalerite, scheelite and gold. The gold varies in fineness from 900 to 930. The Dalny Mine (Leigh, 1964) is in an extensive shear zone in greenstones which are highly altered near the quartz lenses and silicified bodies. The alteration is typical of gold deposits in greenstone exhibiting intense sericitization and carbonatization adjacent the veins and chloritization farther out. CO_2 increases as the quartz bodies are approached. K_2O increases in a similar manner and Na_2O decreases. The mineralization is essentially pyrite, arsenopyrite and minor amounts of chalcopyrite, sphalerite and scheelite. Gold is the only element recovered; it occurs free and in intimate association with arsenopyrite. The grade of the ore averages 0.2 oz Au/ton. The Dawn Mine orebodies are in quartz reefs (veins) in shears in pillow lavas and greenstones that are carbonated, sericitized, chloritized and pyritized near the quartz bodies (Mehliss, 1964). The metallic minerals in the quartz are mainly pyrite and gold with minor amounts of sphalerite and galena. The Patchway Gold Mine is in a quartz vein cutting Archean pillow lava, the principal minerals being native gold, pyrite, galena, sphalerite, chalcopyrite and scheelite (Ward, 1968). The Indarama Mine at Sebakwe (Mehliss, 1968) is of interest because it contains two distinct types of mineralization – an earlier arsenical generation, which impregnates the greenstone walls of the fissures, is followed by a later antimonial generation, which, along with black and white quartz and calcite, forms the fissure fillings. The early generation is represented by pyrite, pyrrhotite, loellingite and arsenopyrite, and the late generations by aurostibite, gudmundite, tetrahedrite, berthierite and stibnite. Gold spans the two generations having been precipitated with both the early and late generations of sulphides and sulphosalts. The mineralization history is very similar to that at Yellowknife, Northwest Territories, Canada.

The deposits in Zaire (Woodtli, 1961*a, b*) are mainly quartz veins in shear and faulted zones in amphibolites, itabirite (iron-formation) and granitoid rocks at Kilo, and gold impregnation deposits in schistose rocks containing carbonate, quartz and albite at Moto.

In Egypt and the Sudan the deposits are varied. At the Gebeit Mine in Sudan (El Boushi, 1972) the orebodies are in quartz-pyrite-arsenopyrite veins in highly sheared, mylonitized and pseudo-schistose silicic volcanics interbedded with tuffs. The wall rocks are highly pyritized, and there is also a development of chlorite, epidote and calcite. Elsewhere in Sudan there are quartz veins, none of which is of economic value, in a variety of Precambrian schists of volcanic derivation near granitic masses. Much gold was won in early times from gold-quartz veins in or associated with Precambrian volcanics and associated rocks, now largely, schists (Emmons, 1937). In Egypt, the El Sid Mine, now largely exhausted, is in quartz veins in basic intrusives, sedimentary schists and gneisses, hornblende migmatite and granite-granodiorite near the contact of the granitic rocks with the schists and gneisses (Derry, 1951). The mineralization comprises quartz, pyrite, galena, sphalerite, chalcopyrite, arsenopyrite and traces of stibnite. The gold is free and grades about 1 oz/ton. Most of the gold in the Egyptian deposits ranged from 730 to 930 fineness.

The details of the metallogenesis of gold in the southeastern desert of Egypt are summarized by Ivanov *et al.* (1973). There appears to be some controversy regarding the age of the auriferous quartz veins with respect to other types of deposits. The writers conclude that at least one phase of gold mineralization is closely related to the Old Volcanics (Archean?), especially their propylitized (chloritized) members. According to El Shazly (1957) the gold veins occur in rocks ranging from early Precambrian schists to late granites. He assigns a late Precambrian age to the gold mineralization.

Tertiary volcanic terranes contain numerous famous gold districts. As examples of these may be mentioned the various deposits in Romania, New Zealand, Fiji, Indonesia, Japan, U.S.S.R., United States and South America.

The gold deposits of Romania occur mainly in faults and fractures that cut Tertiary (Neogene) volcanics in the districts of Brad (Apuseni Mountains) and Baia Mare (Gutăi Mountains) both in Transylvania (Von Palfy, 1911–1912; Streckeisen and Ghitulescu, 1930; Petrulian, 1934; Helke, 1934; Emmons, 1937; Ghitulescu and Socolescu, 1941; Bujor, 1948; Gorzhevskii *et al.,* 1971; Giuscă *et al.,* 1968; Pomârleanu *et al.,* 1972; Giuscă *et al.,* 1973; Cioflică *et al.,* 1973). The volcanics include flows of andesite, dacite and rhyolite, various tuffs, volcaniclastics and interbedded sediments, lying mainly on Mesozoic sediments and crystalline schists (Fig. 27). Volcanic necks of dacite, rhyolite and andesite, and their breccias are favourite sites for the localization of vein clusters (Fig. 28). In this respect the deposits are somewhat analogous to those at Cripple Creek in Colorado. The principal minerals are fine-grained quartz, jasper, chalcedony, calcite, fluorite, rhodochrosite, barite, hematite, pyrite, arsenopyrite, chalcopyrite, galena, sphalerite, alabandite, cinnabar, stibnite, tetrahedrite, bornite, chalcocite, enargite, stephanite, bournonite, argentite, pyrargyrite, proustite, native gold and gold and other tellurides, including sylvanite, nagyagite, petzite, krennerite, hessite

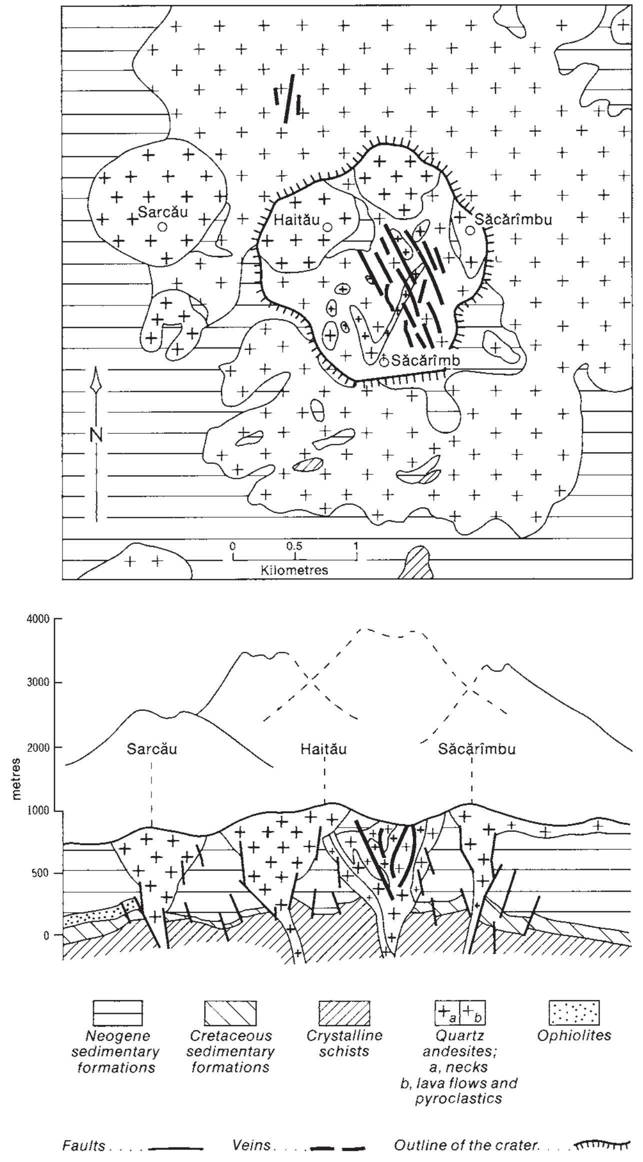
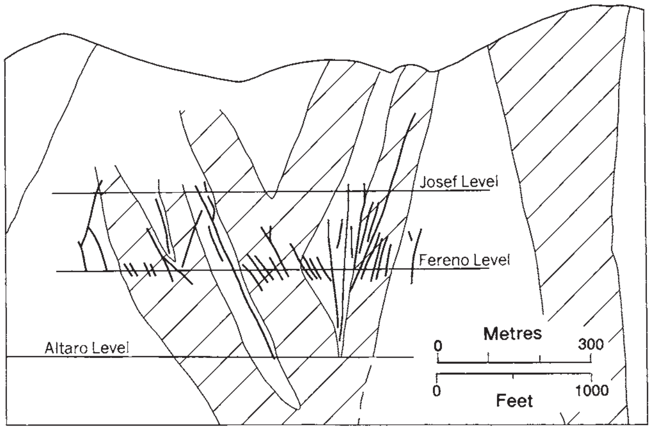


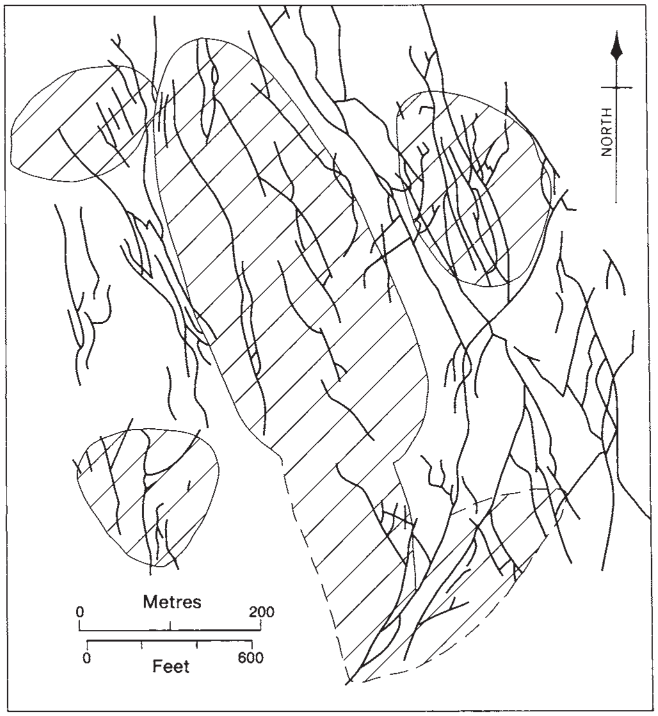
Figure 27. Săcărîmb (Nagyág) volcanic edifice, Apuseni Mountains, Romania (after Cioflica *et al.*, 1973).

and altaite. The propylitic alteration of the volcanics is pervasive and regional in extent. Near the veins and stockworks there is a narrow alteration zone marked by the development of pyrite, carbonates, adularia, sericite, locally alunite and clay minerals. The texture of the veins is usually massive and commonly brecciated; banding is relatively rare and vugs are present but not large. 'Glauch' veins barren of gold are a feature of some of the districts. These veins are older than the ore-bearing veins and are interpreted as having been filled by ascending liquid muds containing fragments of shale and igneous rocks. These unusual veins are sometimes found in other Tertiary volcanic areas in many parts of the world.

The mineralization history of the economic deposits is complex. In the Apuseni Mountains, Cioflică *et al.* (1973)



Generalized section of Săcărîmb (Nagyág) auriferous area



Generalized plan on the level of the Franz Tunnel,
Săcărîmb (Nagyág) auriferous area

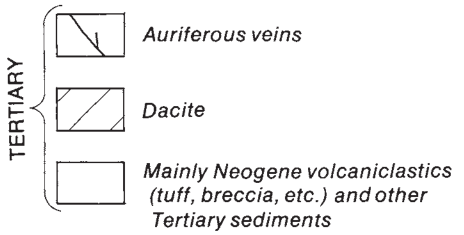


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Figure 28. Generalized plan and section of geological features in the vicinity of the Franz Tunnel level, Săcărîmb (Nagyág), Romania (after Von Palfy, 1912).

recognize three metallogenic phases, oldest to youngest as follows:

1. A gold-silver phase characterized by pyrite, arsenopyrite, sphalerite, chalcopyrite, galena, alabandite, tetrahedrite, pearceite, polybasite, argentite, native gold and marcasite in that paragenetic order. These minerals occur in a quartz, carbonate and rhodocrosite gangue.
2. A gold-silver, base metal sulphide, copper and mercury phase. These deposits are varied and include gold deposits proper, gold deposits with base metal sulphides, porphyry copper mineralization and cinnabar mineralization. The gold deposits proper are characterized by pyrite, marcasite, arsenopyrite, sphalerite, galena, chalcopyrite, alabandite, gold tellurides, tetrahedrite and various other sulphosalts, stibnite, realgar, native arsenic and native gold in that paragenetic order in a gangue essentially composed of quartz, carbonates, rhodochrosite, barite and gypsum.
3. A subordinate base metal sulphide phase characterized in places by tetrahedrite and chalcopyrite, enargite, famatinite, bismuth and germanium minerals, and in places by gold-silver tellurides (sylvanite, hessite) and rarely native gold.

Some of the deposits, especially those with a polymetallic character are markedly vertically zoned as follows from the surface downwards: Au-Ag, Pb-Zn, Cu. In some deposits there is considerable telescoping and several generations of minerals. The geothermometric work by Giuscǎ *et al.* (1968) shows that mineralization proceeded through a large temperature range – 165–269°C for the gold stage and 154–316°C for the polymetallic stage. The grade of the Romanian ores is about 10 ppm Au (0.3 oz/ton). The native gold is relatively rich in silver containing on the average about 25 per cent Ag. The Au/Ag ratio in the deposits as a whole is highly variable especially where silver minerals are present; on the average it is low, about 1:2 to 1:4 judging from the available data. Where the deposits are silver-rich the ratio Au:Ag is in the range of 1:100 to 1:200.

The Tertiary gold deposits of New Zealand occur in the Coromandel Peninsula (Hauraki goldfield) and adjacent regions where andesite and dacite flows of Eocene and Miocene age overlain by Pliocene rhyolites lie on Mesozoic sediments. Several areas have been highly productive, including Waihi, Thames, Coromandel, Kuaotunu, Waitekauri, Komata-Maratoto, Karangahake, Te Aroha and Te Puke. There is an extensive amount of literature on the deposits in these areas, most of which is summarized by Henderson (1930), Emmons (1937) and Williams (1974). Of particular interest are the reports and papers by Park (1897), Fraser (1910), Fraser and Adams (1907), Finlayson (1909), Bell and Fraser (1912), Henderson and Bartrum (1913), Morgan (1924) and Williams (1974).

The deposits at Waihi occurred in a conjugate system of fissures in highly propylitized dacite and andesite. The principal fissure, the Martha, strikes northeast, dips steeply southeast and has been traced for about 1 mi. The subparallel Empire and Royal, and most of the numerous other lodes and fissures, lie to the northeast; they dip steeply northwest and join but, so far as known, do not cross the Martha in depth. Most of the ore-shoots became poorer or terminated altogether at from 600 to 800 ft below sea level.

The orebodies consisted essentially of quartz veins well mineralized with valencianite (orthoclase), calcite, rhodochrosite, pyrite, sphalerite, galena, chalcopyrite, pyrargyrite, acanthite and minor stibnite, native arsenic and molybdenite. The ores were banded and the quartz was colloform (chalcedonic) in some places and lamellar or platy in others. This lamellar or platy quartz is characteristic of some types of Tertiary gold deposits in various parts of the world. Some investigators have suggested that this type of quartz is due to replacement of calcite, but Morgan (1924) thinks this is erroneous. Much of the gold in the Waihi ores was free and there were some tellurides. The grade averaged 0.5 oz Au/ton or more and the Au/Ag ratio averaged about 0.3.

In the Thames area of New Zealand (Fig. 29) the deposits are quartz veins in highly propylitized andesites in a comparatively small downthrow fault block. There was practically no payable ore below a depth of 500 ft from the outcrop of any vein. Fabulous bonanzas characterized the Thames veins, some containing 1 to 6 oz electrum/lb of ore. The principal minerals were quartz, calcite, rhodochrosite, rhodonite, barite, ankerite, pyrite, chalcopyrite, galena, sphalerite, stibnite, molybdenite, cinnabar, argentite, pyrargyrite, hessite, petzite, native arsenic and native gold, the last containing up to 40 per cent silver.

The numerous veins at Coromandel were of the Thames bonanza type. At Te Puke the veins were similar to those at Waihi, but no large bodies of secondarily enriched ore were found as in the latter district. The quartz lodes in the Te Aroha area are mainly in extensive fissures in andesites and dacites. The main fissure or Waiorongomai Buck reef was followed for some 3 mi on strike. It dipped east and consisted of a zone of crushed silicified rock cut by numerous longitudinal and transverse fissures. In places it was 60 ft wide. The mineralization consisted of quartz, calcite, ankerite, rhodochrosite, valencianite (orthoclase), pyrite, chalcopyrite, galena, sphalerite, cinnabar, acanthite, pyrargyrite and native gold, the last ranging in fineness from 645 to 900. The ores of the Karangahake area are similar to those at Te Aroha.

A recent contribution to our knowledge of the Hauraki goldfield by Ramsay and Kobe (1974) is of interest. They studied the silver-gold ores on Great Barrier Island. There, the deposits comprise a number of east-striking, quartz-filled, mineralized fissures that transect andesites and an unconformably overlying siliceous sinter deposit of upper Pliocene to Pleistocene age. The wall-rock alteration exhibits a crude zoning consisting of a general propylitization in the andesites with argillic assemblages and silicification developed close to the veins. The endogene ore minerals comprise pyrite, marcasite, arsenopyrite, chalcopyrite, sphalerite, rare galena and tetrahedrite, acanthite, electrum, silver, chlorargyrite, pyrargyrite, proustite, polybasite-pearceite, argyrodite, aguilarite, naumannite, realgar and stibnite. The principal supergene minerals are limonite, hematite, covellite, native silver, kermesite and cervantite. The electrum is approximately 500 fine, while the Au/Ag ratio of the deposits as a whole is 0.033. The ore is seleniferous, some of the polybasite containing up to 3 per cent Se. The argyrodite is, likewise, selenium-bearing, as is also the galena. The two selenides, aguilarite and naumannite, are relatively rare. The presence of the germanite and argyrodite is of interest, considering that certain thermal waters in

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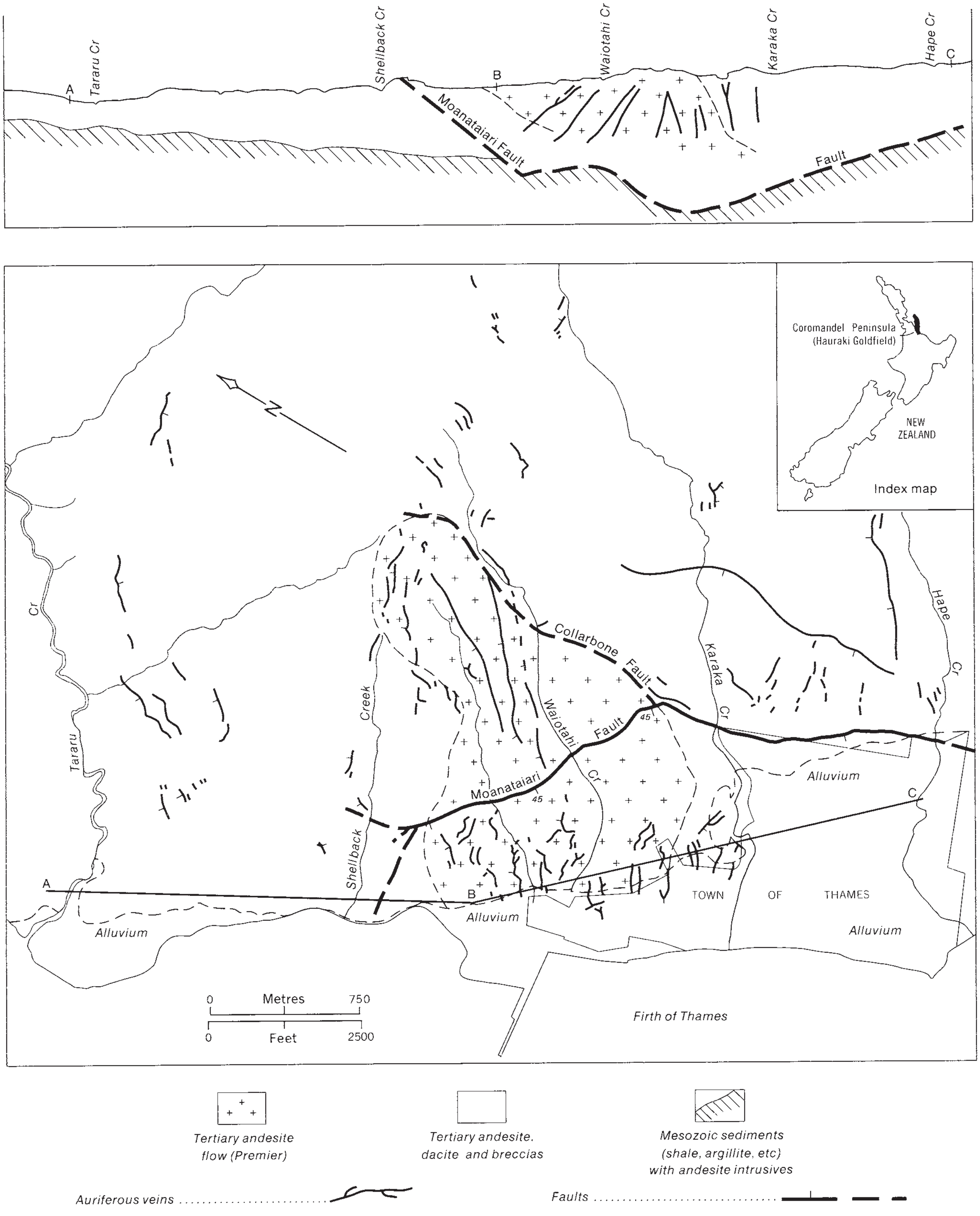


Figure 29. Generalized plan and section of the Thames goldfield, Coromandel Peninsula, New Zealand (after Fraser, 1910).

North Island, New Zealand (Taupo zone) are germanium bearing (Browne, 1969). Ramsay and Kobe (1974) considered that the maximum depth of deposition was of the order of 500 m and regarded the mineralization as subvolcanic and of Upper Pliocene or Pleistocene age. The paragenetic sequence of ore minerals involved a number of episodes that overlapped one another. Initial deposition was characterized by pyrite and marcasite, which continued intermittently through the subsequent base metal, silver sulphosalt, selenide and stibnite stages. A very late hypogene episode resulted in the deposition of chlorargyrite and widespread kaolinite. Deposition of electrum appears to have commenced with the silver-sulphosalt stage and increased with the closing stages of mineralization.

From the descriptions of the various mining regions both recent and past the Hauraki deposits appear to be crudely zoned with cinnabar mineralization near the surface, gold-silver mineralization also near the surface and passing successively downward into lead-zinc zones and then into copper-rich zones.

The Tertiary gold deposits of Fiji are all veins and lodes (Ibbotson, 1962; Houtz and Phillips, 1963; Rickard, 1966). Those in the Vatukoula field (Emperor Gold Mine) in northern Viti Levu (Blatchford, 1953; Markham, 1960; Cohen, 1962; Ibbotson, 1967; Denholm, 1967) occur in numerous narrow shear and shatter zones that vary in attitude from subhorizontal flatmakes to vertical shears. These cut gently dipping basaltic flows, tuff beds and ash beds intruded by numerous andesite dykes, all of which form part of a Tertiary volcanic caldera. The productive veins appear to favour the basalts on the western flank of the caldera, although many of the shears straddle the contact of the caldera and the underlying basalts. The andesite dykes are heavily propylitized, but the basalts and other volcanics only exhibit marked propylitic effects near the quartz lodes. The intervening basalt between shears is generally quite fresh. The lodes of the Emperor Mine are composed mainly of crustified and vuggy quartz accompanied by some carbonate. The metallic minerals include pyrite and arsenopyrite, both of which are auriferous, pyrrhotite, marcasite, chalcopyrite, galena, sphalerite, tetrahedrite-tennantite, native gold, native tellurium and a number of Au-Ag tellurides. Native gold is relatively rare and when present is dendritic and leafy. The native tellurium contains up to 0.1 per cent Au. The tellurides, native tellurium and native gold are late minerals in the paragenetic sequence. The gold content of the ores ranges from 0.25 to 1 oz/ton, and the Au/Ag ratio of the ores averages about 3. The fineness of the hypogene microscopic gold is about 940 according to Stillwell (1949). The Emperor Mine produces both gold and tellurium. The lodes when first found exhibited only shallow oxidation zones in which fine wire gold of great fineness (960) was encountered. As in New Zealand there were no significant placers associated with the Vatukoula goldfield. Deposits similar to those at Vatukoula occur on Vanua Levu at the former Mount Kasi Gold Mine (Green, *in* Fisher, 1973). There, the basaltic and andesitic pyroclastics are considerably altered by propylitization, silicification and sericitization, adjacent to the quartz lodes and veins that contain essentially quartz, carbonate, pyrite, barite, native gold and minor tellurides.

The most productive gold deposits in Indonesia are in Tertiary rocks. The deposits include those at Paleleb, Soemalta, Totok and Bolang Mongondou in the north arm of Celebes, those in the Lebong district in Sumatra and those in western Java, among which are the Tjikotok and Tjipitjoeng districts (De Jongh, 1930; Van Bemmelen, 1970). The deposits are mainly quartz veins and lodes and silicified zones in faults, fractures and sheeted zones in Tertiary andesites, porphyritic diorites, rhyolite, trachyte, and their associated tuffs and slaty sediments. The mineralization is mostly quartz and carbonates commonly manganiferous, with variable amounts of arsenopyrite, pyrite, pyrrhotite, sphalerite, galena, chalcopyrite, acanthite, pearceite, polybasite, tennantite, enargite (luzonite), native gold (commonly electrum) and gold-silver tellurides (hessite, sylvanite, petzite). Rhodonite, rhodochrosite and manganese-silver compounds are common in some veins; zeolites, some manganiferous, have been noted in a few veins; and silver and other selenides in the Lebong district. The gold content of the veins is variable but is commonly 0.5 oz/ton or more. The Au/Ag ratio ranges from 0.16 to 1. Some of the ores are highly seleniferous, the selenium being largely concentrated in sulphides, particularly in acanthite, galena and arsenpolybasite (Kieft and Oen, 1973).

The gold deposits in the Philippines have recently been described by Bryner (1969). They include the enargite-luzonite-telluride deposits at Lepanto, Luzon, localized along the intersection of an unconformity and a fault zone; the quartz-telluride-gold vein deposits of the Baguio district, Luzon; and a quartz–base metal sulphide deposit in the Paracale district, Camarines Norte. Lepanto and some of the Baguio district deposits are spatially related to centres of Tertiary explosive volcanic activity.

The Lepanto deposit is a pencil-shaped polymetallic body encased in a silicified and argillized envelope in late Miocene to early Pliocene dacitic pyroclastics and Cretaceous-Paleogene metavolcanics. The economic minerals of interest are enargite, luzonite, tennantite and Au-Ag tellurides. The Au/Ag ratio is about 1:4. The Baguio deposits are mainly veins in fractures and are composed essentially of quartz, calcite, rhodonite, rhodochrosite, pyrite, base metal sulphides, Au-Ag tellurides, native gold, stibnite and cinnabar. Some of the veins contained considerable amounts of gypsum and anhydrite. Many of the deposits are in andesites and dacites cut by numerous dioritic dykes and plutons. The Paracale-Gumaus Mine works veins containing pyrite, chalcopyrite, sphalerite, galena and gold in a quartz gangue. Many of the veins are in granodiorite beneath an ultramafic body. A pale greenish bleaching is widespread in the vicinity of the more productive veins.

The gold deposits of Taiwan are mainly in Tertiary volcanics and sediments (Huang, 1955, 1960, 1972, 1973). The gold-copper deposits of the Chinkuashih Mine occur as irregular lenses or pipes in silicified Miocene sandstone or dacite. Fissure-filling and impregnation or replacement are the principal processes of ore formation. Sheeted and brecciated structures are common. The ore minerals are pyrite, enargite, luzonite, bournonite, sphalerite, cinnabar and native gold, accompanied by the gangue minerals quartz, barite, alunite, kaolinitic clay, and minor amounts of diaspore and sulphur. The ores are characterized by crustification, ringore and drusy structures. Wall-rock alteration is marked. From the orebodies outwards there are three zones – a silicified zone, an argillized or alunitized zone and a chloritized and carbonated zone. Supergene enrichment is not present except for superficial enrichment of native gold of residual origin.

The Wutanshan area, adjacent to the Chinkuashih Mine, is underlain chiefly by Miocene sediments intruded by dacite, both greatly fractured by faulting. The ore deposits in this area occur as fissure-fillings of thin, lenticular form in dacite, and partly in sandstone and shale. The ore is composed mainly of quartz and pyrite, accompanied by minor barite, calcite, manganocalcite, kaolinitic clay, galena, sphalerite, marcasite and native gold. Crustification and drusy structures are common. In contrast with the Chinkuashih deposits, enargite, luzonite and alunite are absent, and quartz gangue is abundant. Three alteration envelopes associated with the deposits are defined: from the veins outward, there are zones of silicification, argillization and chloritization-carbonatization. Alunitization is absent and silicic alteration is not as common as in the Chinkuashih area. The deposits are of epithermal origin and were probably formed in late Pleistocene time. They show the same genetic and age relationships as the Chinkuashih deposit.

In Japan, gold deposits of Tertiary age are widespread (Tatsumi, 1970; Nishiwaki *et al.,* 1971; Kitami, 1973), being localized in the zone of andesite, basalt, rhyolite, dacite and associated tuffs and sediments known as the Neogene 'Green Tuff Region' by the Japanese geologists. Nearly all of these rocks are gently dipping and highly faulted. In addition they are extensively altered on a regional scale, the principal alteration effects being those of propylitization and argillization. Nishiwaki *et al.* (1971) recognized nine types of Neogene gold-silver deposits in Japan. These occur as fissure veins, stockworks and stockworks in intensely silicified rock. The types are as follows:

(1) Those rich in base metals with an Au/Ag ratio equal to about 1. Their mineralogy comprises pyrite, sphalerite, chalcopyrite, galena, hematite and gold (electrum);

(2) Those rich in chalcopyrite and mined mainly for copper;

(3) The argentite (acanthite) type typified by sphalerite, galena, pyrite, chalcopyrite and gold. Gangue minerals are quartz, adularia, sericite, clay minerals and calcite. The Au/Ag ratio ranges from 0.025 to 0.1;

(4) The manganese mineral type characterized by abundant rhodochrosite and rhodonite plus the mineral assemblage and Au/Ag ratios described in (3) above;

(5) Deposits with high amounts of silver sulphosalts such as polybasite and pearceite and a mineral assemblage as in (3) above;

(6) An intermediate type between types (5) and (7);

(7) Deposits with sulphosalts having a low silver content;

(8) The luzonite-enargite type characterized by the presence of luzonite-enargite, pyrite and quartz. These deposits are very poor in silver minerals and generally lack galena and sphalerite;

(9) Telluride-bearing deposits. These are rare. The mineral assemblage is usually tellurides, luzonite-enargite, tetrahedrite, pyrite, quartz and barite.

Vertical zoning is a conspicuous feature in some of these deposits, the general downward zonation being Au-Ag, Pb-Zn, Cu. A number of producing gold mines occur in southern Kyushu that are representative of some of these types and will serve as examples (Matsukuma, 1962; Taneda and Mukaiyama, 1970; Wakabayashi *et al.,* 1973).

The Kushikino deposit near the city of the same name is an anastomosing series of quartz veins in fractures in gently dipping propylitized andesite (Fig. 30). The footwalls of the veins are highly silicified whereas the hanging walls exhibit extensive sericitization. Both types of alteration are also associated with a development of small amounts of adularia, calcite and pyrite. Two types of ores are present in the Kushikino deposit; one contains mainly milky medium-grained quartz with native gold (electrum) and small amounts of scattered sulphides; the other is a fine-grained chalcedonic quartz with thin black bands (Ginguro ores) of fine-grained sulphides, sulphosalts, selenides and electrum, mainly pyrite, chalcopyrite, marcasite, sphalerite, galena, acanthite, pyrargyrite, stephanite, polybasite, naumannite, tetrahedrite and electrum. The medium-grained quartz ores contain up to 1 oz Au/ton and the Au/Ag ratio ranges from 0.25 to 1. The Ginguro ores are rich and usually contain >1 oz Au/ton; their Au/Ag ratio ranges from 0.03 to 0.1.

The Kasuga Mine near Makurazaki City represents a somewhat different type of Tertiary gold deposit. It consists of a stockwork of quartz veins and stringers in a porous silicified zone developed in andesite tuff, tuff breccia and tuffaceous shale. The core of the mineralized area is represented by a porous mass of fine-grained quartz. Surrounding this there is a dickite-kaolin zone, which grades imperceptibly through kaolinized rock into unaltered tuffs and other rocks (Fig. 31). The minerals in the quartz veins and stringers and silicified zone are mainly enargite and native gold. Native sulphur occurs in places. The grade of the quartz vein stringer zones of the deposits is about 0.6 oz Au/ton. The highly siliceous part of the deposits averages about 0.1 oz Au/ton and is used as a flux in copper smelters.

The Tertiary gold deposits of the U.S.S.R. occur mainly in the far east (Radkevich, 1966; Radkevich *et al.,* 1965; Shilo *et al.,* 1969; Rozhkov, 1971*b,c,d*; Zagruzina, 1972; Anoshin and Kepezhinskas 1972; Magakian, 1972; Kuznetsov and Panifilov, 1974) particularly in the mobile belt and areas underlain by Tertiary volcanics and other rocks in Kamchatka (Aprelkov and Kharchenko, 1968), the lower reaches of the Amur River (Yugai, 1967) and the Okhotsk-Chukotsk volcanic belt (Sidorov, 1965). The Tertiary rocks in this vast territory are varied and include basalts, andesites, dacites, trachytes, rhyolites and the corresponding tuffs. Some of the deposits are in Mesozoic rocks but are of Neogene age. Other deposits are confined solely to the Tertiary rocks, large stretches of which show the characteristic propylitization and argillization common to Tertiary rocks throughout the world. The deposits are, likewise, varied, but most are systems of quartz veins or stockworks in andesites and dacites and silicified zones with quartz veins in tuffs. To generalize it can be said that the chief minerals are quartz, carbonates, pyrite, arsenopyrite, the various base metal sulphides, tetrahedrite, stibnite, various silver minerals, minor scheelite, native gold and electrum. A few of the deposits contain a little cassiterite and others have small amounts of cinnabar. Adularia figures in the wall-rock

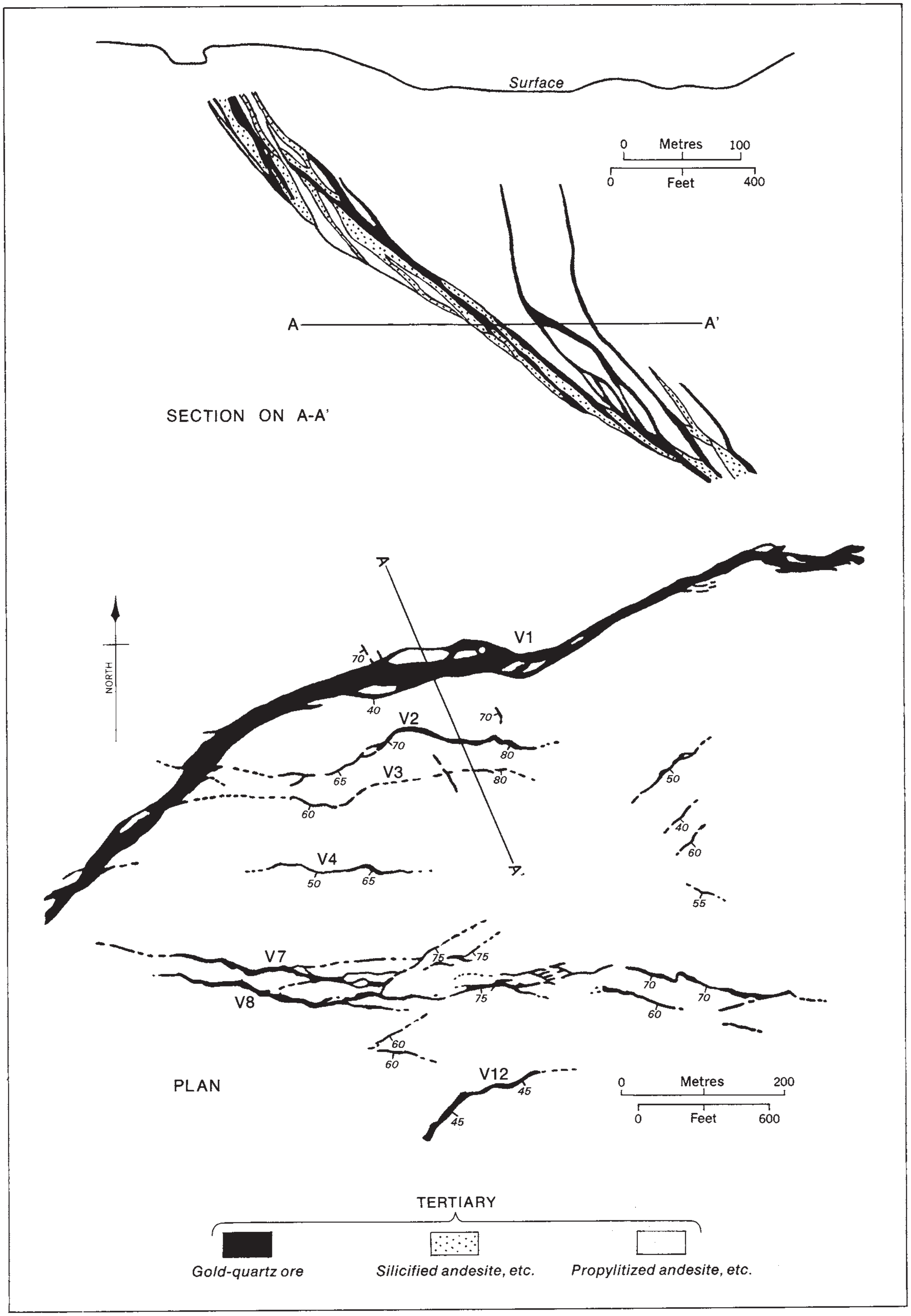


Figure 30. Generalized plan and section of the vein systems of the Kushikino Mine, southern Kyushu, Japan (after Taneda and Mukaiyama, 1970).

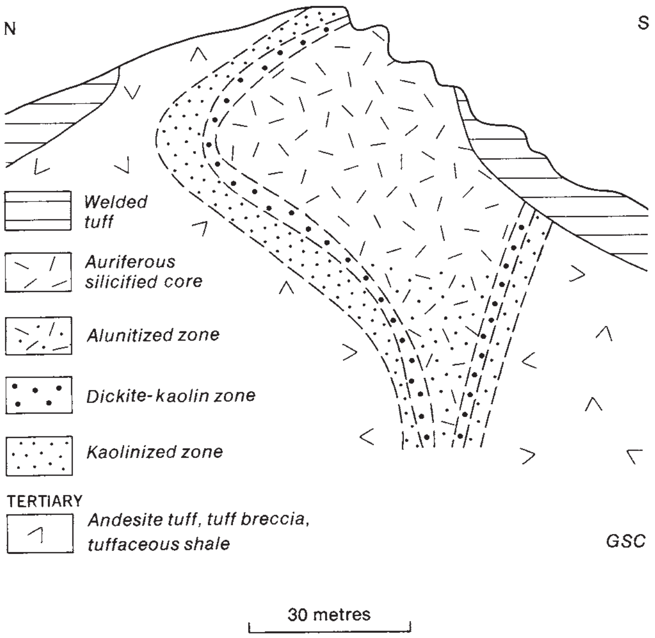


Figure 31. Generalized section showing the ore zone and alteration halos of the Honko deposit of the Kasuga Mine, southern Kyushu, Japan (after Taneda and Mukaiyama, 1970).

alteration zones and vein minerals in some veins and alunite in others. Braunite, the manganese silicate, is present in some veins and zeolites and epidote are characteristic of some veins and their alteration halos. The deposits are generally silver rich, the fineness of the gold averaging about 700.

In detail, the auriferous deposits of the far eastern U.S.S.R. can be classified into four categories: gold-quartz, gold-rare metal, gold-silver and gold-sulphide (Shilo *et al.*, 1969).

The gold-quartz deposits are mainly veins and irregular bodies generally related to folding. They are particularly common in the Mesozoides of the northeastern U.S.S.R. Their mineralization consists essentially of quartz, carbonates, pyrite, arsenopyrite, galena, sphalerite, sulphosalts and native gold. The age of many of these deposits is apparently middle to late Mesozoic (Zagruzina, 1972).

The gold-rare metal deposits are mainly veins and lodes associated with faults and fracture systems and are said to be related mainly to granitoid intrusions of the volcanoplutonic gabbro-andesite-granodiorite clan. The mineralization occurred in at least two stages – greisenization with the development of wolframite and molybdenite followed by quartz, carbonates, disseminated base metal sulphides, cassiterite (wood tin in places), wolframite, scheelite, bismuth tellurides, gold and gold-silver tellurides. The age of this mineralization is late Cretaceous-Paleogene.

The gold-silver deposits are veins and stockworks associated mainly with deep faults. Their mineralization comprises essentially quartz, commonly colloform banded, rhythmically crystalline banded, drusy, or platy, base metal sulphides, hematite, stibnite, acanthite and gold. Some deposits are transitional to the gold-rare metal polymetallic types of deposits. Propylitization is characteristically developed in the volcanic host rocks of many of the gold-silver deposits. Most of the gold-silver deposits are late Cretaceous to Paleogene in age.

The gold-sulphide deposits are complex mineralogically, consisting essentially of quartz, albite, carbonate, chlorite, hydromica, pyrite, chalcopyrite, galena, sphalerite, tetrahedrite and gold. The sulphides may make up 30 to 40 per cent of the ores. Propylitization of the andesite host rocks of the gold-sulphide deposits is common and widespread. The age of the deposits is apparently late Cretaceous–Paleogene, mainly the latter.

As many as four stages may be distinguished in the formation of some of the deposits. The first stage was one of silicification, chloritization and epidotization of the host rocks. Among the ore minerals, pyrite and hematite were introduced at this stage. During the second stage, the greater part of the quartz veins was formed, and sulphides of lead, zinc and copper were deposited along with silver and gold. The adularia also appeared during this stage. Thereafter, tectonic movements reopened the fissures, fractured the previously deposited ores and vein material and new quartz veins were deposited. During this third stage, some galena, sphalerite, chalcopyrite and probably also gold were deposited. During the fourth and last stage there was no influx of ore minerals – only the carbonates were precipitated in the central parts of the earlier veins.

One of the deposits, the Belaya Gora, in the gold-bearing region of Nizhyni Priamur, has been extensively investigated (Mel'nikov and Mel'nikova, 1970; Petrovskaya *et al.*, 1971*d*). The deposit is composed of impregnations and stockworks of minerals in the vent and near-vent facies of Oligocene volcanics comprising felsite porphyries, liparites, trachytes and dacites. These break through relatively flat-lying andesite and basalts. The mineralization consists principally of fine-grained quartz and clay minerals, adularia, gold and small amounts of sulphides including pyrite, arsenopyrite, chalcopyrite, sphalerite, galena, hematite, pyrargyrite, proustite, native silver, tetradymite, cinnabar and metacinnabar. There are also small amounts of wood tin. The Au/Ag ratio of the deposit is 1:4. The host rocks are extensively altered. There is a more or less regional propylitization; near the deposits there is much silicification, pyritization, argillization, some adularization, sericitization, carbonatization and chloritization dependent on the rock type affected.

The elements enriched in the Tertiary deposits of the Soviet far east include: Cu, Ag, Au, Ba, Zn, Cd, Hg, (B), Ga, La, Sn, Pb, As, Sb, Bi, (Se), Te, Mo, W, Mn, Fe and S. Those in parentheses are relatively rare or local.

Tertiary gold deposits in the Western Cordillera of North America are confined mainly to Mexico and the United States. Few deposits in Mexico are essentially gold deposits. Most, such as those at Pachuca, Real del Monte and Guanajuato (Veta Madre), are rich silver deposits with a little gold as a byproduct (Echegoyén *et al.* (1972)). Their oxidized zones in places, however, were apparently rich in gold.

El Oro district in Mexico, some 70 mi northwest of the capital, is noted for its Tertiary gold lodes in fault fissures (Flores, 1920). These cut Mesozoic pyritic shales intruded by Tertiary andesite sills. The veins were oxidized and then covered by later flows of andesite. The mineralization comprises fine-grained, often banded and crustified quartz, calcite, pyrite, sphalerite, acanthite and other sulphides. The ores average about 0.5 oz Au/ton and 10 oz Ag/ton. The main deposits are now exhausted. Somewhat similar deposits in Tertiary andesites and dacites were mined near Hostotipaquillo and elsewhere in Mexico (Ridge, 1968; Albers and Kleinhampl, 1970; Roberts *et al.,* 1971).

In the western United States there are numerous famous gold camps closely associated with Tertiary volcanics; their rich gold-silver ores are now largely exhausted. As examples, we may mention deposits in the Black Mountains of Arizona; De Lamar, Idaho; Rawhide, Jarbidge, Tonopah, Goldfield and Virginia City (Comstock Lode), Nevada; Cripple Creek and the San Juan region, Colorado; and Republic in Washington. These exhibit a varied geology and mineralogy that can be touched upon only briefly here. All deposits are veins, lodes or stockworks in faults, fractures, sheeted zones or shattered zones in Tertiary volcanic terranes. Most are silver-rich with a low to very low Au/Ag ratio. Fabulously rich gold-silver bonanzas were features of many of the deposits. Many of the veins were attended by extensive wall-rock alteration effects including pyritization, sericitization, chloritization, silification, carbonatization, and the development of adularia and alunite.

The deposits in the Black Mountains of Arizona near Oatman were veins and lodes along fault fissures, mainly in Tertiary andesite heavily chloritized and sericitized near the veins. The veins were beautifully crustified and filled with chalcedonic quartz, calcite, fluorite, adularia, minor base metal sulphides, acanthite, silver sulphosalts and finely disseminated gold. At De Lamar, Idaho, the veins in fissures and faults cut mainly rhyolite that exhibits silicification, development of adularia and pyritization near the veins. Mineralization consisted essentially of quartz, calcite, adularia, fluorite, minor base metal sulphides, acanthite and naumannite (Ag_2Se). The grade of the ore was about 0.5 oz Au/ton and the Au/Ag ratio is 0.05.

The gold veins at Jarbidge, Rawhide, Gold Circle, Round Mountain, Beatty and National, Nevada are essentially similar. They occurred in faults and fractures that cut rhyolite or, in places, more basic Tertiary volcanics and tuffs and contained essentially quartz, adularia, calcite and small amounts of pyrite, arsenopyrite, base metal sulphides, acanthite, tetrahedrite, pyrargyrite, other silver sulphosalts and naumannite. At National, stibnite is abundant. Some veins contained small amounts of barite, fluorite and clay minerals, mainly kaolinite and halloysite. The native gold was silver rich, often only 500 to 600 fine, and the Au/Ag ratios of the deposits as a whole ranged from 0.02 to 0.3. The grade of most deposits was about 0.5 oz Au/ton.

The silver-gold deposits at Tonopah, Nevada are replacement veins and lodes occupying faults and fractures that cut a complex series of Tertiary tuffs, breccias, rhyolite, trachyte and andesite flows injected by rhyolite plugs (Spurr, 1905; Bastin and Laney, 1918; Nolan, 1930, 1935; Bonham and Garside, 1974). The wall rocks are extensively altered near the veins as the result of silicification, sericitization and the development of adularia. This alteration grades outward into a kaolinite-montmorillonite-chlorite-carbonate-albite alteration phase and finally into the fresh wall rock. The veins were defined mainly by assay and in the case of the famous Mizpah vein were as much as 40 ft wide. The chief hypogene minerals in the veins and lodes were quartz, adularia, sericite, rhodonite, barite, manganiferous calcite, electrum, argentite, polybasite, pyrargyrite, selenides, huebnerite, scheelite, cinnabar, pyrite, sphalerite and galena. The Au/Ag ratio changed from about 1:85 in the central part of the district to less than 1:100 in the western and eastern extremities of the district. The ores, especially the oxidized ones, were exceedingly rich running hundreds of ounces of silver and tens of ounces of gold to the ton in some shoots.

Supergene enrichment of the lodes was notable in the Tonopah district reaching depths of 700 ft or more in places. The supergene minerals developed included limonite, kaolin, hyalite, turquoise, wavellite, dahllite, gypsum, jarosite, wulfenite, native gold and silver, covellite and a variety of silver halides, chlorargyrite in the upper parts of the veins, bromargyrite (embolite) in the middle and iodargyrite in the lower parts (Burgess, 1911). Some of the argentite, polybasite and pyrargyrite were considered by early investigators to be of supergene origin.

The upper limit for the age of the Tonopah mineralization is given as 20.4 m.y. and the lower limit as 17 m.y. by Bonham and Garside (1974).

At Goldfield, some 30 mi south of Tonopah, an intrusive sill of dacite invades Tertiary trachyandesite, rhyodacite, latite and rhyolite flows and tuffs, overlying Mesozoic quartz monzonite that intrudes Ordovician black argillite and shale (Ransome, 1909). Searls (1948) considers that the dacite, in which a high proportion of the gold veins occur, is actually a flow in the volcanic series. Ashley (1974) interprets the geology of the Goldfield district as a volcanic centre marked by a ring fracture that probably delineates a small caldera of Oligocene age (Fig. 32*a* and *b*). Alteration of the volcanics is extensive on a regional scale consisting mainly of silicification, argillization and alunitization. The age of the mineralization is Tertiary (20.6–21.1 m.y.) as determined by potassium-argon dating of primary alunite (Silberman and Ashley, 1970) and fission track methods (Ashley and Silberman, 1976). The orebodies were irregular sheets, pods and pipes with indefinite boundaries within linear silicified zones in the southwestern corner of the extensive alteration zones (Fig. 32*c* and *d*). These silicified zones and their contained ore sheets called "ledges" by Ransome (1909, 1910) consisted of quartz, pyrite, alunite, kaolinite, marcasite, sphalerite, bismuthinite, famatinite, tennantite, goldfieldite (Te-bearing tetrahedrite) and various gold tellurides (petzite, hessite, sylvanite). The average grade of the ore near the end of the life of the deposits was about 0.3 oz Au/ton, but much higher grades, up to 100 oz Au/ton or more, were common in the near surface parts of the lodes. The Au/Ag ratio of the ores was about 3 judging from the old records.

The famous Comstock Lode at Virginia City some 20 mi southeast of Reno, Nevada was one of nature's largest concentrations of gold and silver (Becker, 1882; Reid, 1904–1906; Bastin, 1922). The lode, which developed in a great fault fissure with upward projecting spurs, is of Tertiary age and cut mainly andesite (Fig. 33).

The wall rocks were intensely propylitized and sericitized. Most of the orebodies were bonanza shoots and consisted of intensely crushed quartz, some calcite, pyrite, chalcopyrite,

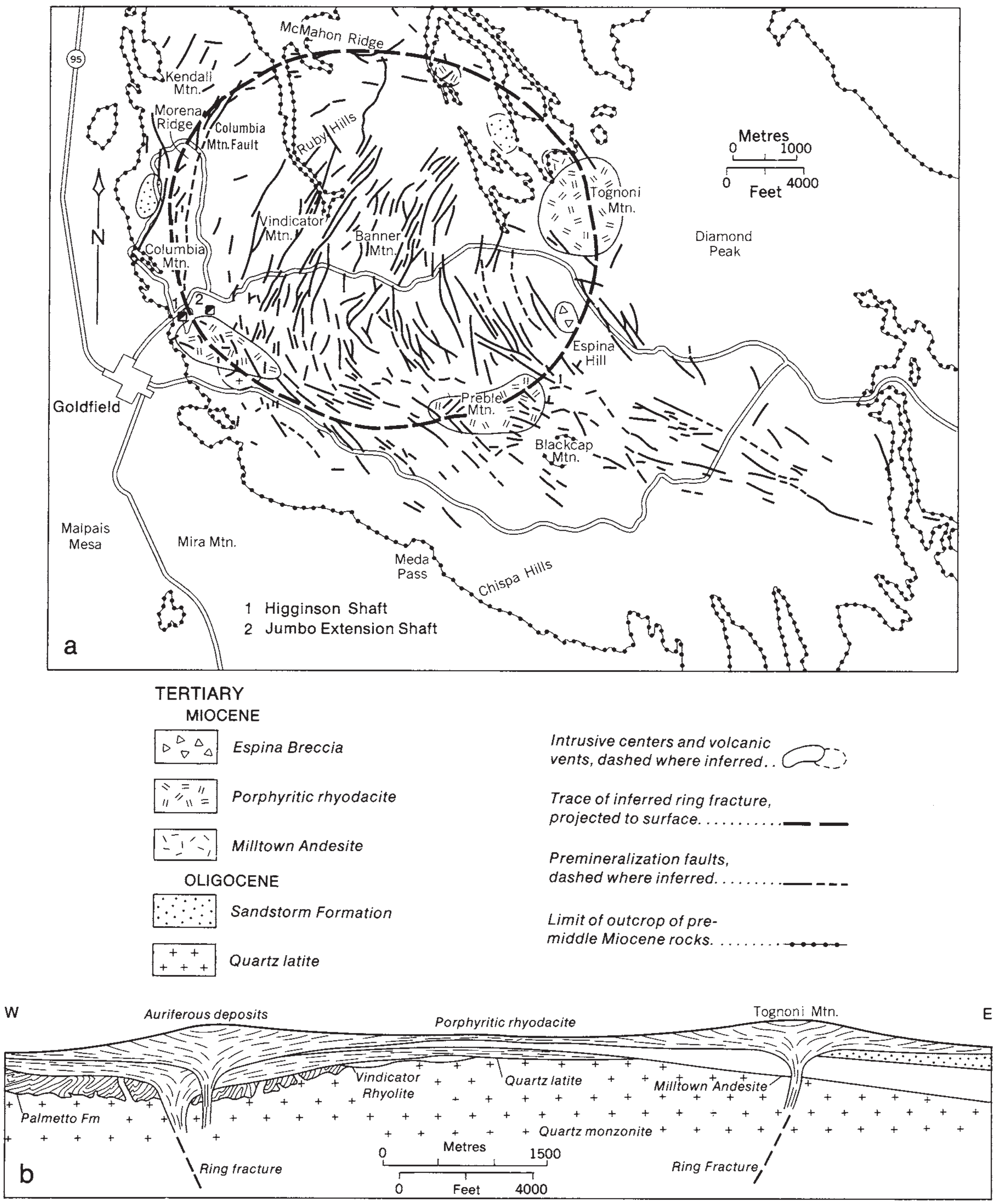


Figure 32. (a) Plan showing premineralization faults and intrusive centres for premineralization volcanic units, Goldfield district, Nevada (modified from Ashley, 1974). (b) Diagrammatic cross-section through the Goldfield volcanic centre prior to shingle faulting and ore deposition (modified from Ashley, 1974).

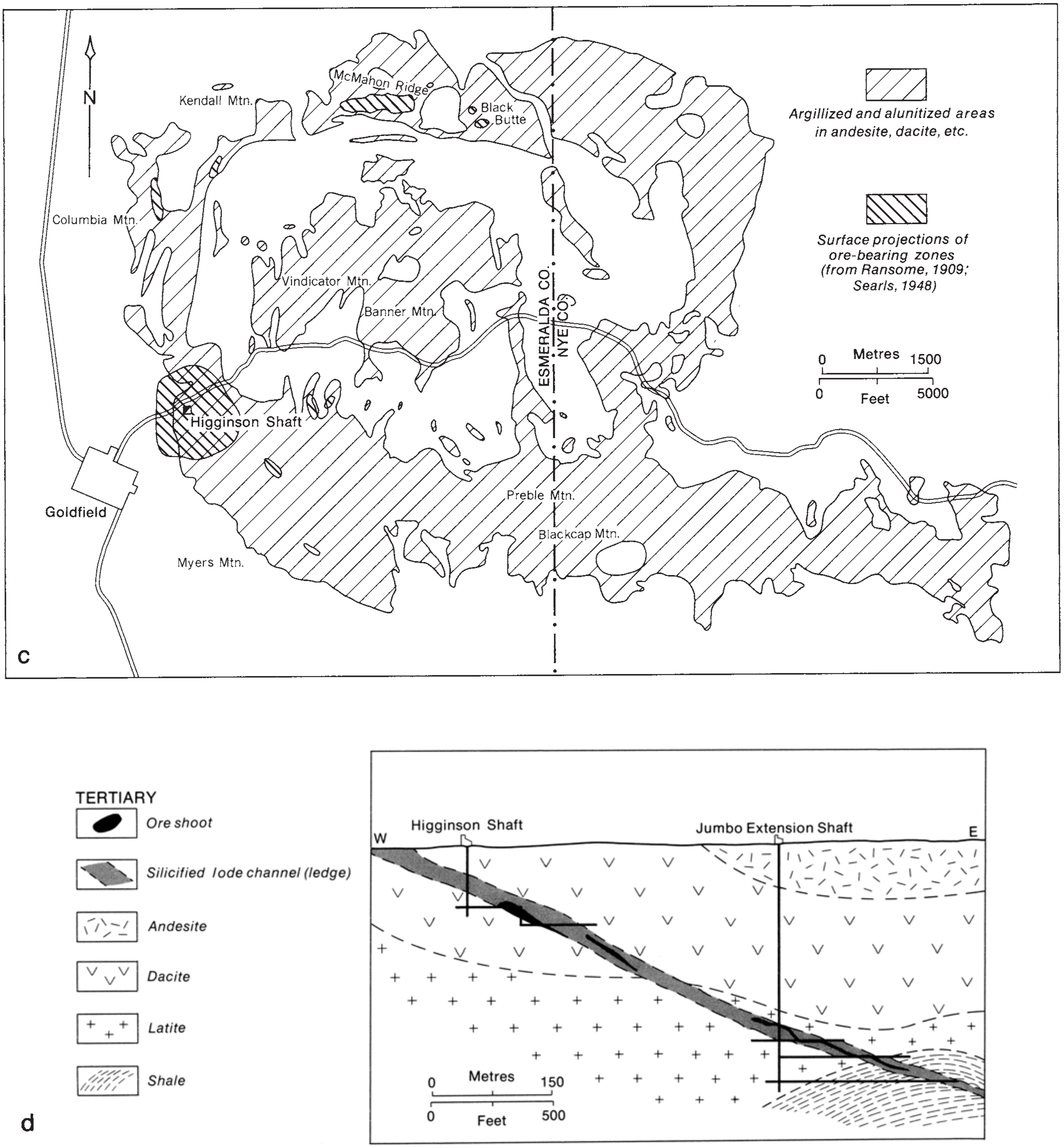


Figure 32. (c) Plan of Goldfield district, Nevada showing mineralized and altered zones (modified from Jensen *et al.*, 1971). (The argillized and alunitized areas enclose the productive and unproductive auriferous ledges.) (d) Vertical section of the Mohawk-Jumbo lode, Goldfield, Nevada (modified from Turner, 1915).

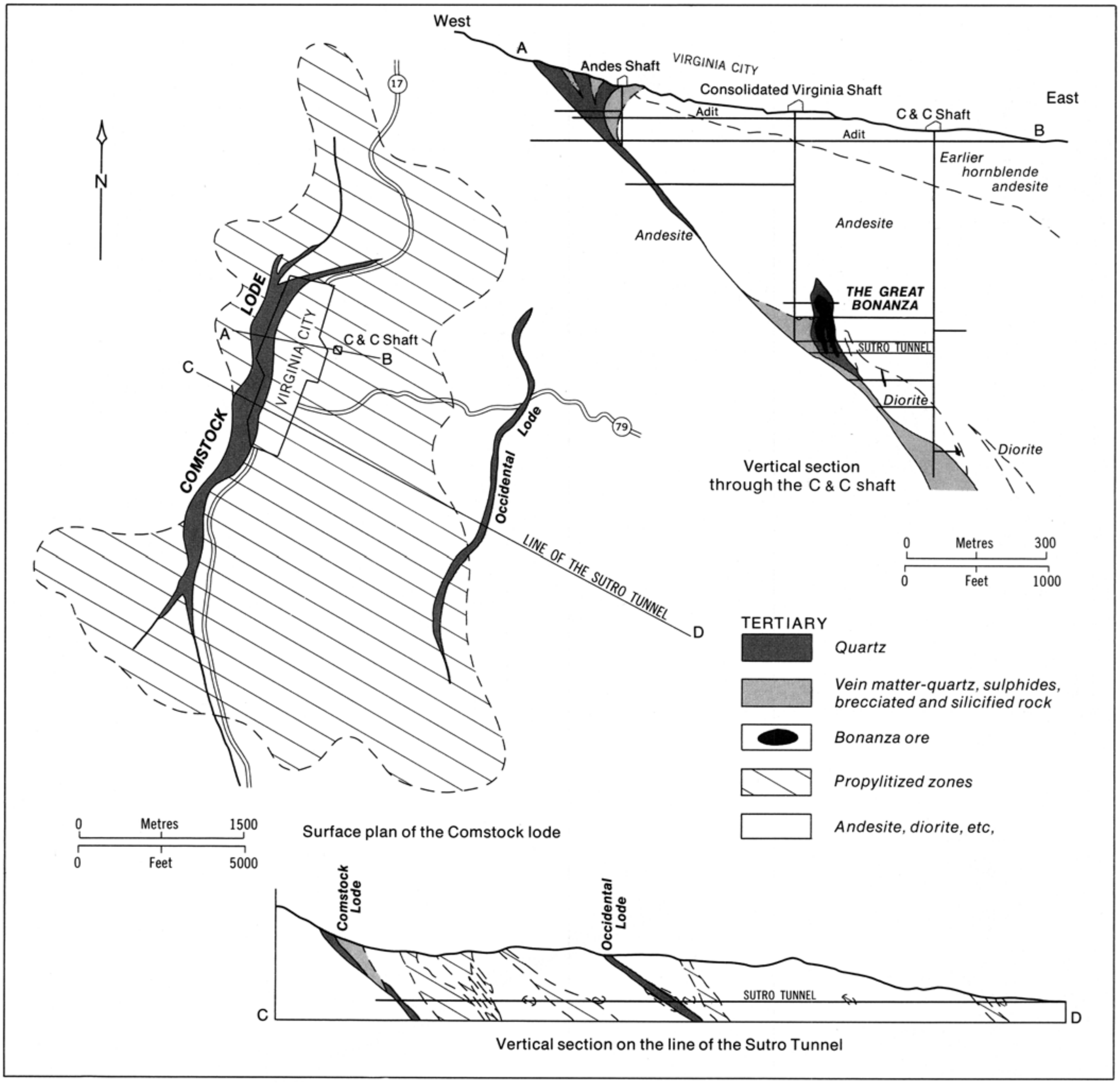


Figure 33. Generalized geological plan and sections of the Comstock Lode, Virginia City, Nevada (modified from Becker, 1882, and others).

sphalerite, galena and abundant gold, electrum, acanthite, polybasite and other silver sulphosalts. The Au/Ag ratio of the ores was about 0.025. In the deeper levels, flows of hot (170°F) calcium sulphate waters and rock temperatures of 115°F made mining of the lode difficult.

The San Juan region in southwest Colorado contains a number of important mineral districts, many of which contain polymetallic deposits with only small amounts of gold and silver. A number of deposits, however, mostly small but exceptionally high grade and now largely exhausted, were essentially gold-silver producers, including Telluride, Ouray, Silverton, Rico, Creede, La Plata, Bonanza, Lake City and Needle Mountains. The rugged San Juan Mountains are underlain chiefly by Tertiary tuffs, andesite, latite and rhyolite poured out on a basement of folded Mesozoic and Paleozoic sediments lying on Precambrian gneisses and other rocks (Steven, 1968; Burbank and Luedke, 1968; Steven and Lipman, 1976). The deposits are veins, sheeted zones and replacements mostly in the volcanics and tuffs, mineralized with quartz, rhodochrosite, rhodonite, barite, fluorite, galena, sphalerite, tetrahedrite, enargite, pearceite, gold tellurides and native gold. Some veins contain a little bismuthinite, molybdenite and huebnerite. Propylitization and sericitization are marked close to the veins. The ores in the Telluride district were in fissures in tuffs, andesite and rhyolite and contained crustified and drusy quartz, calcite, siderite, rhodochrosite, adularia, barite, fluorite, pyrite, galena, sphalerite, chalcopyrite, polybasite and native gold. The ores averaged about 0.3 oz Au/ton and the Au/Ag ratio of the ores was about 0.03. In the Ouray district the famous Camp Bird lode averaged about 1 oz Au/ton. The lode intersected tuff and andesite and consisted of beautifully banded and crustified quartz, rhodochrosite, calcite, fluorite, native gold, gold tellurides and a few per cent of galena, pyrite and sphalerite. The Camp Bird lode is one of many gold, silver and base metal deposits in the Silverton district in faults, fissures and brecciated zones related to the Silverton Cauldron (Fig. 34). The ores of the Creede district (Steven, 1968, 1969) were veins in fault fissures in rhyolite and consisted of banded amethystine quartz, hematite, barite, rhodochrosite, chlorite, argentiferous galena, sphalerite, chalcopyrite, pyrite and acanthite. The gold content averaged about 0.1 oz/ton and the silver about 12 oz/ton, giving an Au/Ag ratio of 0.008. The age of the mineralization (24.6 ± 0.3 m.y.) is latest Oligocene-Miocene (Steven, 1969; Bethke *et al.,* 1976).

In a recent contribution to the mineralization history of the western San Juan Mountains, Colorado Lipman *et al.* (1976) state that the ore deposits formed intermittently in middle to late Tertiary time (from about 30 to 10 m.y. ago) during essentially the same period as that of associated igneous activity. The mineralization occurred recurrently during the waning stages of evolution of several precaldera central volcanoes and also after the formation of the Uncompahgre, San Juan, Silverton and Lake City calderas. The rich deposits of the Silverton Caldera were formed later than the caldera and are closely related in space and time to volumetrically minor intrusions of quartz-bearing silicic porphyry. Lipman *et al.* (1976) stress the point that the time relationships of the volcanism and mineralization seem to preclude any significant genetic tie between the major mineralization and implacement of the caldera-forming magmas. The calderas, therefore, served mainly as structural controls for the mineralization, which seems to be closely related in some as yet unknown manner with minor intrusions of the quartz porphyry type.

The Bodie mining district lies near the eastern margin of the Bodie Hills in California, close to the Nevada border. The country rocks consist mainly of Tertiary andesite, dacite, rhyolite and welded tuffs lying on Mesozoic and Paleozoic sediments and late Mesozoic granitic rocks (Clark, 1970). The mineralization is Tertiary (7.2–8.6 m.y.) as determined by potassium-argon dating on adularia (Silberman *et al.,* 1972) and consists of quartz veins containing adularia, some pyrite, minor base metal sulphides and abundant finely disseminated gold, rich in silver. Most of the veins were unproductive below 1000 ft.

Numerous other gold-silver deposits associated with Tertiary volcanic centres occur in the western United States. Two, Cripple Creek, Colorado and Republic, Washington, are briefly described below; short descriptions of others can be found in Emmons (1937).

Auriferous mineralization of Tertiary age is relatively uncommon in British Columbia and Yukon although as noted elsewhere some of the deposits in the Boundary District of British Columbia and the Mount Nansen deposit in Yukon may be of Tertiary age. Another deposit of undoubted Tertiary age is the Dusty Mac prospect located about 1 mi east of Okanagan Falls, British Columbia (Church, 1973).

The Dusty Mac deposit is a lenslike zone in highly fractured silicified Eocene volcanic rocks and sedimentary debris (White Lake Formation) marked in places by the development of small quartz veins. The mineralization consists mainly of quartz, of at least three ages, disseminated pyrite, native gold and native silver, the last probably supergene in part. Some of the quartz veins carry minor bornite and chalcopyrite. The deposit is marked by a limonitic gossan. A published statement by Dusty Mac Mines quoted by Church (1973) indicates 67 790 tons of ore averaging 0.23 oz Au/ton and 4.97 oz Ag/ton. In a more recent report (Northern Miner, Oct. 9, 1975, v. 61, no. 3, p. 1) the reserves are quoted as 102 413 tons averaging 0.24 oz Au/ton and 4.29 oz Ag/ton with 10 per cent dilution.

Church (1973) considers that the following events led to the formation of the deposit:

1. Development of dilations in major shears.
2. Filling of the dilations with quartz, accompanied by gold and silver mineralization.
3. Late-stage movement in the shear zones resulting in brecciation of the quartz and intermixing of the quartz with crushed andesite wall rocks.

In South America there are numerous gold districts associated with Tertiary volcanic terranes. As an example one may mention the Zaruma mining area in Ecuador described by Billingsley (1926) and Goossens (1972). There the veins cut the Tertiary Portovelo andesite formation, which is intruded by small bodies of dacite, rhyolite and granodiorite. The mineralization is essentially quartz and calcite with pyrite, argentiferous galena, sphalerite, chalcopyrite and native gold. The ore ran 0.25 to 1.0 oz Au/ton and 1 to 3 oz Ag/ton.

Contents

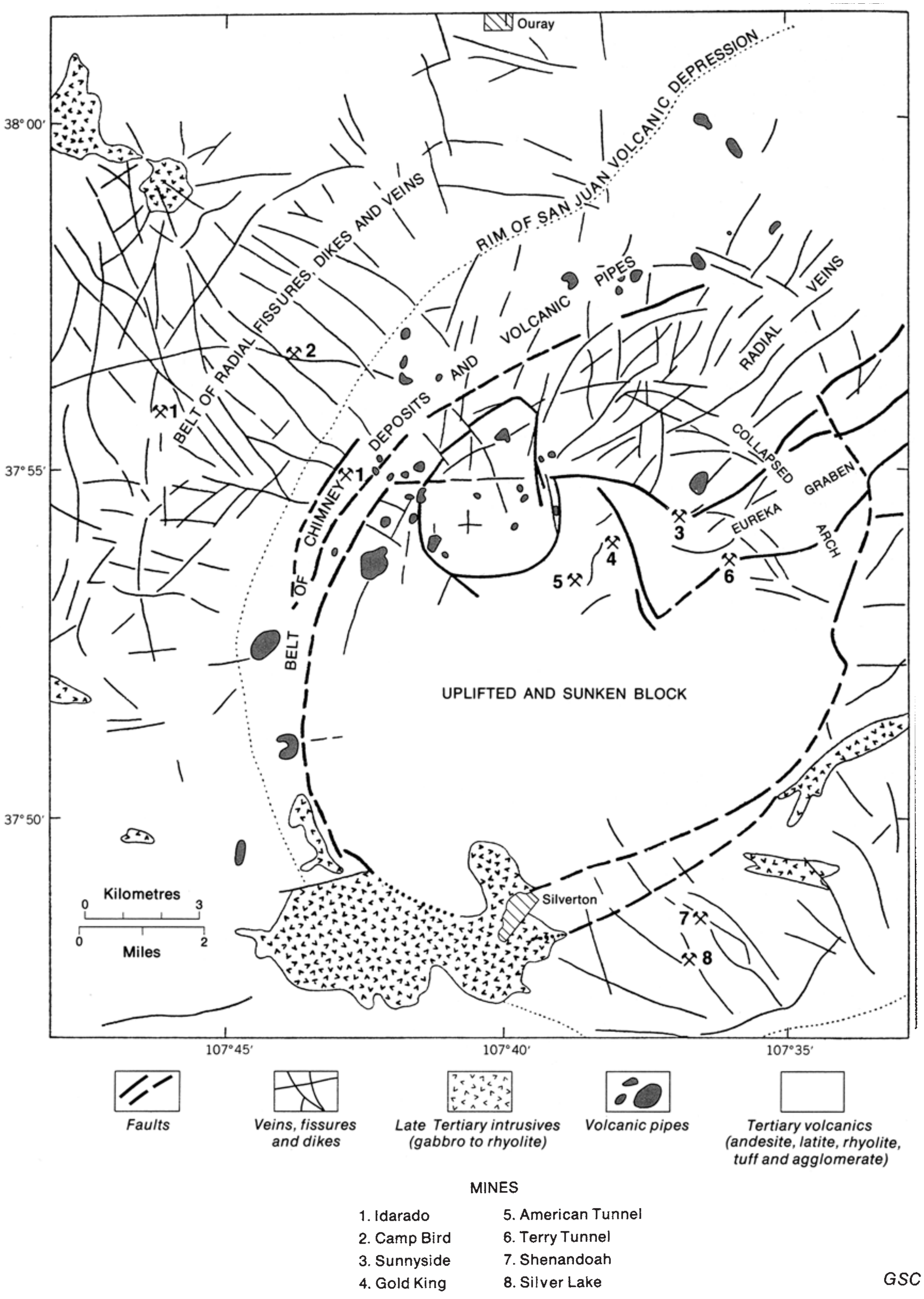


Figure 34. Structural map of Silverton Cauldron showing relationship of veins, faults and mines (modified from Burbank and Luedke, 1968).

Since the time of the Conquistadores, Colombia has produced more than a billion dollars in gold (50 million ounces), two thirds from placers and the remainder from lodes. Most of the lodes are probably of Tertiary age and occur principally in the Department of Antioquia but also in Chocó, Caldas, Nariño, Cauca and Tolima. The country rocks of the lodes, stockworks, mantos, impregnation zones and veins include granites and other granitic rocks, porphyries, sediments and volcanics ranging in age from Precambrian to Tertiary. In the Titiribí district of Antioquia some of the deposits occur in or near highly propylitized and pyritized andesites (Sierra Veta andesite) that are slightly auriferous. The mineralization in the various deposits in Colombia consists essentially of quartz, calcite, dolomite, pyrite, arsenopyrite, sphalerite, galena, bournonite, chalcopyrite, jamesonite, stephanite, ruby silver, cinnabar, argentite, tetrahedrite, stibnite and free gold. Alteration associated with the auriferous bodies comprises mainly sericitization, carbonitization and pyritization. The native gold varies in fineness from 340 to 920; the average gold grade of the deposits as a whole was about 0.3 oz/ton (10 ppm). Some deposits averaged 1 oz Au/ton or more. The silver content ran up to 10 oz/ton (340 ppm) or more in some shoots. The Au/Ag ratios of many of the deposits averaged about 0.35. The average fineness of the placer gold is about 800. A summary of the gold deposits of Colombia with a bibliography is given by Singewald (1950).

Gold-telluride and gold-selenide deposits

These deposits are veins, stockworks, sheeted zones and mineralized pipes commonly in Tertiary volcanic rocks, although some are known in older rocks. The economic minerals in the telluride deposits are mainly gold-silver tellurides, frequently with relatively little free gold except in the oxidized zones. The economic minerals in the selenide deposits are native gold closely associated with various selenides, some silver-bearing and others silver-gold-bearing (fischesserite). Both types of deposits are relatively rare.

Cripple Creek, Colorado is the best known example of the gold telluride deposits (Lindgren and Ransome, 1906; Loughlin and Koschmann, 1935). The country rocks are Precambrian granites and gneisses broken through by a great mass of Tertiary volcanic rocks representing a large volcano (Fig. 35). The core of this volcano is composed of tuffs and breccia of latite-phonolite, which are cut by dykes and masses of phonolite, syenite, monchiquite and vogesite. The deposits are veins, mineralized sheeted zones, replacements in breccia and along fissures and irregular pipes in mineralized breccia (Fig. 36). These cut both the Precambrian and Tertiary rocks,

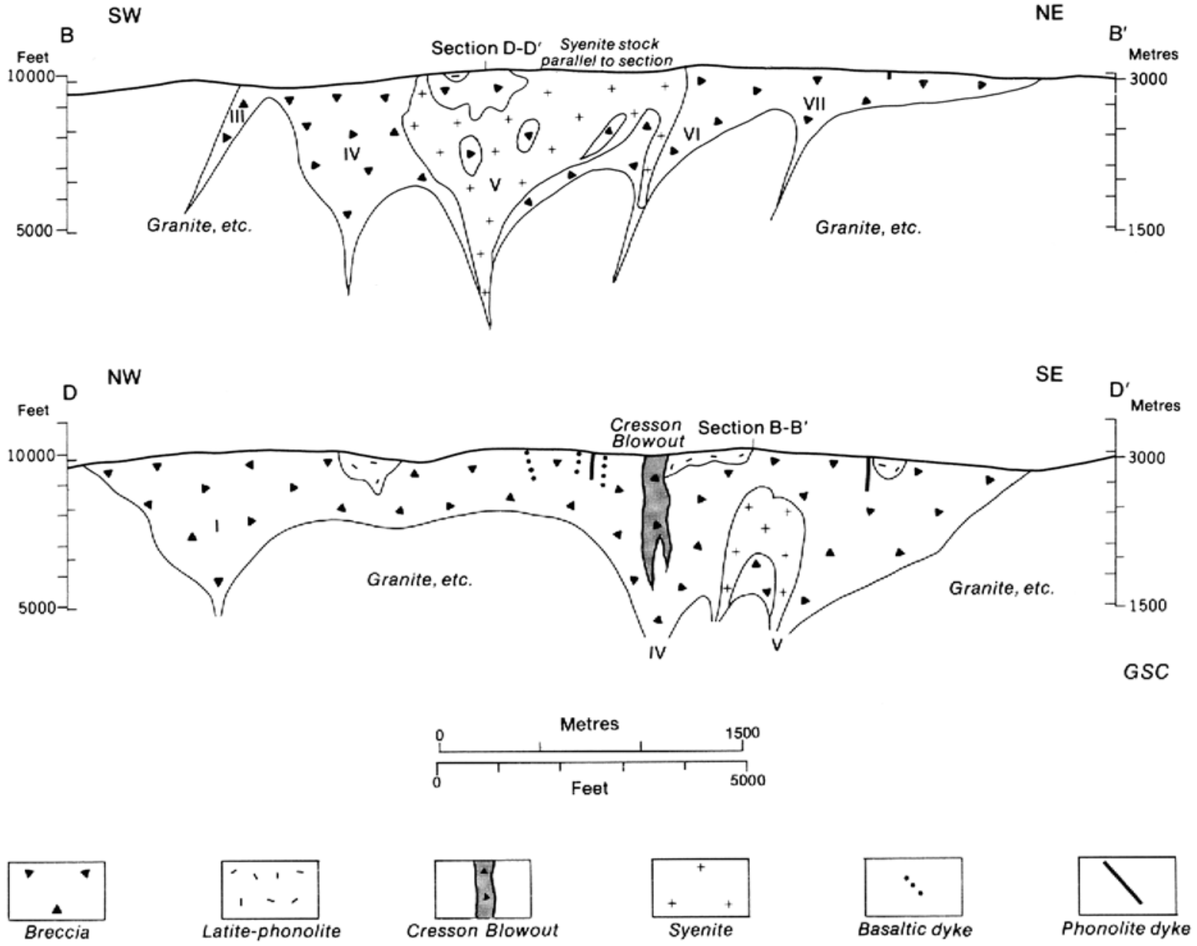


Figure 35. Generalized cross-sections through the Cripple Creek Crater, Cripple Creek, Colorado. Section BB' is approximately at right angles to Section DD'. Roman numerals indicate subcraters (modified from Loughlin and Koschmann, 1935).

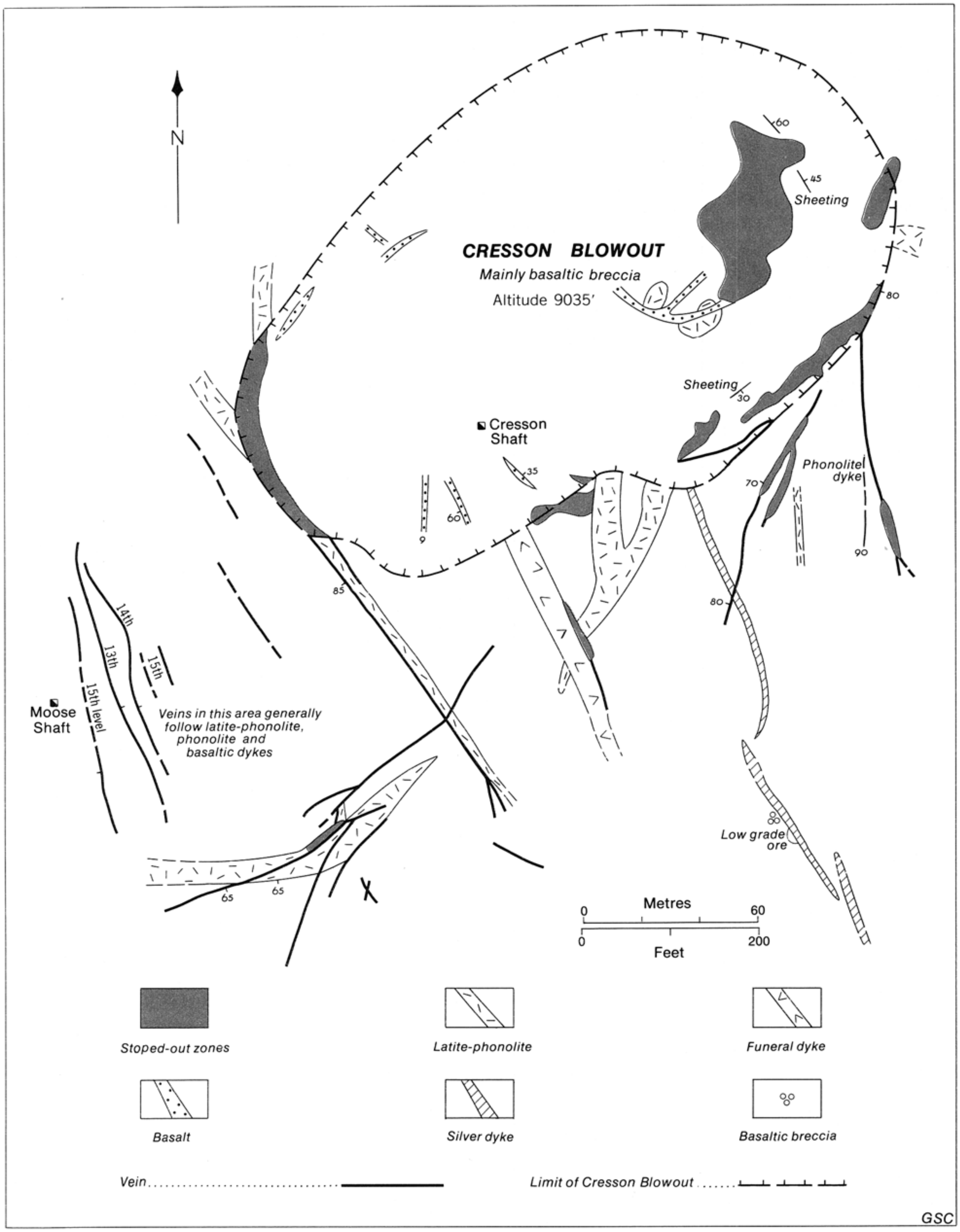


Figure 36. Plan of level 10 of the Cresson Mine and of the lower levels of the Moose Mine, showing relations of Cresson Blowout to the breccia and dykes of the main crater and to veins and irregular orebodies (after Loughlin and Koschmann, 1935).

but are best developed in the latter. The principal ore mineral is calaverite, $AuTe_2$, with a silver content generally less than 4 per cent. There is practically no hypogene native gold. Associated with the calaverite are small amounts of sylvanite, petzite, pyrite, sphalerite, galena, tetrahedrite, stibnite, cinnabar, molybdenite and minor amounts of wolframite (huebnerite). Coloradoite has been identified in the primary ore, and acanthite, native gold and jarosite in the oxidized zone (Hildebrand and Gott, 1974). The gangue is quartz, fluorite, carbonate and roscoelite (the vanadium mica). The vein structure is drusy. The alteration is pyritization, carbonatization and propylitization. Adularia is developed in some veins.

Loughlin and Koschmann (1935) recognized three stages in the formation of the Cripple Creek orebodies. The first stage was characterized mainly by the deposition of jasper and porous aggregates of quartz and adularia and fine-grained, massive mixtures of fluorspar and quartz accompanied by some coarsely crystalline pyrite. The characteristic minerals of the second stage are quartz, fluorspar, fine-grained pyrite, dolomite or ankerite, celestite, roscoelite, sphalerite, galena, tetrahedrite, tellurides of gold and in some places tellurides of silver and copper. The tellurides are late minerals generally following all of the other minerals of the second stage. The third general stage is represented mainly by openings containing clear to smoky quartz, chalcedony, fine-grained and radiating pyrite crystals, calcite and locally cinnabar.

The deposits of Cripple Creek are now largely exhausted. During their lifetime they produced some 20 000 000 oz of gold or more and 2 000 000 oz of silver. The fabulously rich calaverite 'vugs' or 'caverns' in the Cresson 'blowout' yielded more than 1 000 000 oz of gold.

Gold-silver tellurides are important ore minerals in a number of other deposits throughout the world. In these, however, the tellurides are generally subsidiary to native gold. Examples include Kirkland Lake, Ontario, Canada; Kalgoorlie, Western Australia; Brad, Romania; and Vatukoula, Fiji. Most of these deposits are described above or in the following sections.

The gold-selenide deposits are rather rare. There are, however, examples at Republic in Washington (Umpleby, 1910; Lindgren and Bancroft, 1914; Wright, 1947; Full and Grantham, 1968), in the Radjang-Lebong goldfield in Sumatra, Indonesia and at the Kushikino Mine, Kagoshima Perfecture, Japan (Mukaiyama and Izawa, 1964). Most of the deposits are veins, stockworks and pipes in Tertiary or younger andesites. The principal gangue is quartz and calcite, sometimes adularia, usually in banded and colloform arrangements or in fine-grained intergrown aggregates. The principal ore minerals are native gold, often high in silver, electrum, various silver, lead and copper selenides such as aguilarite, naumannite and berzelianite, pyrite, tetrahedrite, chalcopyrite, galena and sphalerite. These minerals are often fine grained and form distinctive black streaks, wisps, crusts and bands in the quartz. These bands are rich in gold and silver, often assaying hundreds and thousands of ounces of gold and silver to the ton. The alteration attending the veins is generally silicification, pyritization or propylitization. The Au/Ag ratio of the deposits in the Radjang-Lebong field varies from 0.01 to 1.

Auriferous veins, lodes, sheeted zones and saddle reefs in faults, fractures bedding plane discontinuities and shears, drag folds, crushed zones and openings on anticlines essentially in sedimentary terranes; also replacement tabular and irregular bodies developed near faults and fractures in chemically favourable beds

These deposits are widespread throughout the world and have produced a large amount of gold and silver. They are developed predominantly in sequences of shale, sandstone and greywacke dominantly of marine origin. Such sequences are invariably folded, often in a complex manner, metamorphosed, granitized and invaded by granitic rocks, forming extensive areas of slate, argillite, quartzite, greywacke and their metamorphic equivalents. Near the granitic bodies various types (kyanite, andalusite, cordierite) and quartz-mica schists and hornfels are developed, and these grade imperceptibly into relatively unmetamorphosed slates, argillites, quartzites and greywackes marked by the development of sericite, chlorite and other low-grade metamorphic minerals. Most of the gold deposits are developed in the lower grade facies. Few economic deposits occur in the granitic batholiths or large stocks that invade the greywacke-slate sequences.

The principal gangue mineral in these deposits is quartz, frequently ribbonned, with a glassy, white, grey, to black colour. Feldspar, micas, chlorite and minerals such as rutile are subordinate. Among the metallic minerals, pyrite and arsenopyrite are much the commonest, but galena, chalcopyrite, sphalerite and pyrrhotite also occur. Molybdenite, bismuth minerals and tungsten minerals are local. Stibnite occurs in abundance in a few deposits but is relatively rare in most deposits. Acanthite, tetrahedrite-tennantite, and other sulphosalts are not common in these deposits. Carbonates, mainly calcite and ankerite, are common but not abundant. The valuable ore minerals are native gold, generally low in silver, auriferous pyrite and auriferous arsenopyrite. Tellurides are relatively rare, and aurostibite is an uncommon mineral in these deposits.

A few deposits in this category are tabular or irregular replacement (disseminated) bodies developed in carbonate rocks or limy argillites and shales. The principal minerals developed in these deposits include quartz, fluorite, pyrrhotite, pyrite, arsenopyrite, sphalerite, galena, chalcopyrite and stibnite.

As a general rule the wall-rock alteration effects associated with these deposits are minimal and the quartz veins, saddle reefs and irregular masses are frozen against the slate, argillite or greywacke wall rocks. In places thin zones of mild chloritization, sericitization and carbonatization are present. Some veins are marked by thick black zones (up to 6 in.) of tourmalinized rock. Disseminated pyrite and arsenopyrite are common in the wall rocks of most of these deposits. This pyrite and arsenopyrite is commonly auriferous.

The elements exhibiting a high frequency of occurrence in this type of gold deposit include Cu, Ag, Mg, Ca, Zn, Cd, (Hg), B, (In), (Tl), Si, Pb, As, Sb, (Bi), S, (Se), (Te), (Mo), W, (F), Mn, Fe, (Co) and (Ni). Those in parentheses have a low to very low frequency of occurrence.

The sedimentary piles in which these deposits occur are marked by extensive developments of shales, argillites and slates, all containing abundant pyrite. These are invariably enriched in all of the elements contained in the deposits. In addition the clastic sediments in the sedimentary piles including conglomerate, greywacke and sandstone commonly have higher than normal amounts of gold, probably of detrital origin. These, together with the black pyritiferous sediments, are probably the source beds for the elements in the deposits. As the various structures developed in the sedimentary piles, especially along fault and fracture systems and on the noses of anticlines (saddle reefs), their dilatancy induced the diffusive flow of silica, gold and other elements into these sites where they were partitioned into the series of minerals we now observe in the veins and lodes. In places chemically receptive rocks have precipitated quartz, gold and other minerals from diffusion currents moving gold and gangue elements through the rocks.

In detail the precise relationships of the gold deposits in this category to granitic bodies invading the sedimentary terranes are often not entirely clear in many auriferous belts. In many sedimentary terranes the metamorphic, granitization and vein-forming processes appear to be coeval or nearly so. In other regions, however, particularly in greywacke-slate terranes, some of the quartz deposits appear to be truncated by the granitic bodies, and xenoliths of the quartz veins containing arsenopyrite and pyrite occur in the granitic rocks. In a few places (e.g., Yellowknife) some of the auriferous quartz veins are cut by pegmatites. Such relationships are often observed where there are two ages of granitic rocks in the terrane as in the Precambrian Yellowknife Supergroup and in the Ordovician Meguma Group of Nova Scotia. Commonly the first phase is a biotite granite whereas the second is a muscovite granite usually with a plethora of associated pegmatites. Where these geological features are present the sequence of events seems to have been:

1. Initial stage of folding of greywacke and slate with the concomitant effects noted in 2.
2. Rise of the geotherms through the sedimentary pile due to metamorphism and granitization at depth. This is attended by the migration of silica, sulphur, arsenic, gold and other constituents into available dilatant zones to form the saddle reefs, leg reefs and interbedded veins with their contained auriferous sulphides and native gold.
3. Continued folding resulting in the corrugation of the quartz veins, formation of quartz boudins, ptygmatic veins and a general crushing and recrystallization of the quartz. During this period remobilization and reconcentration of the initial gold in dilatant sites (shoots), commonly as the native metal, may take place in the quartz bodies. In addition further increments of gold, sulphur, arsenic, silica and other constituents may be provided by the prevailing diffusion currents.
4. Continued granitization at depth followed by the injection of high level granitic stocks and small batholiths. The development of pegmatites commonly takes place during this stage.
5. Late stage minor folding and faulting.

Deposits in sedimentary terranes are widespread in Canada, United States, France, U.S.S.R., Australia and South Africa. Only a few characteristic examples will be described.

The Precambrian sediments of the Yellowknife Supergroup in the Yellowknife district, Northwest Territories comprise mainly slate, argillite, quartzite and greywacke, and their metamorphic equivalents, various quartz-mica schists, near granitic batholiths and stocks. All of the sediments were intricately folded in an isoclinal manner, then cross folded, yielding basin and dome structures and finally faulted. The gold deposits occur as:

1. Quartz veins in contorted schist zones and faults that transect the sedimentary beds.
2. Quartz veins and small stockworks in schist zones and fractures that parallel the sedimentary beds. These comprise quartz veins and stockworks in ruptured and sheared beds and bedding planes, dragged slate beds, contacts and saddle reefs on the noses of folds.
3. Quartz veins and sheeted zones in ruptured and sheared axes of isoclinal folds.
4. Quartz veins and stringer zones in other irregular fractures and openings without any continuity or special relationships.

The Ptarmigan (Fig. 37) and Burwash deposits are quartz veins and lenses in small faults that cut greywacke and slate beds at a large angle (Boyle, 1961*a*). Wall-rock alteration is minimal (*see* page 240). The gangue is colourless to grey massive quartz with native gold and minor amounts of tourmaline, pyrite, sphalerite and galena. The grade of the ore was about 0.5 oz/ton, and the Au/Ag ratio of the ores ranged from 3 to 8.

The Thompson-Lundmark Gold Mine some 40 mi northeast of Yellowknife obtained its ore from large quartz veins lying parallel to the bedding of the knotted quartz-mica schists and slates (Fortier, 1946, 1947; Lord, 1941*a,b*, 1951). The wall-rock alteration is minimal, and the mineralization consists mainly of quartz and abundant native gold with small amounts of tourmaline, feldspar, pyrite, arsenopyrite, pyrrhotite, chalcopyrite, galena and sphalerite. The grade of the various ore-shoots ranged from 0.4 to 1.5 oz Au/ton and the Au/Ag ratio averaged about 5. Some of the veins in the vicinity of the Thompson Lundmark Mine are of interest, since they are traversed by pegmatites.

The ore shoots of the Camlaren Mine at Gordon Lake (Henderson and Fraser, 1948; Lord, 1951) are in saddle reefs and legs on the nose of a pitching anticline (Fig. 38). The grade of the ore was about 0.75 oz Au/ton and the Au/Ag ratio of the ores ranged from 5 to 8. The mineralization consisted essentially of quartz with some ankerite, native gold and small amounts of pyrite, chalcopyrite, galena and sphalerite. Literally thousands of narrow quartz veins, saddle reefs and legs occur in the slaty beds between more massive greywacke and quartzite in the Gordon Lake basin. All contain gold, but few are of economic grade and tonnage.

The Consolidated Discovery Yellowknife Mine in the Giauque Lake area of Northwest Territories developed and mined orebodies mainly in highly folded and crenulated metasediments near the nose of steeply dipping volcanics (Wiwchar, 1957). One of the orebodies (the north zone vein) had a saddle shape (Fig. 39); other zones were irregular. The vein mineralization was essentially quartz with small amounts of oligoclase, pyrrhotite, pyrite, muscovite, sericite, actinolite, chlorite and rare occurrences of scheelite, sphalerite, galena, chalcopyrite and andalusite. The gold was free and coarse, and the last mineral to crystallize. The wall-rock alteration consisted mainly of a band a few inches wide next to the vein

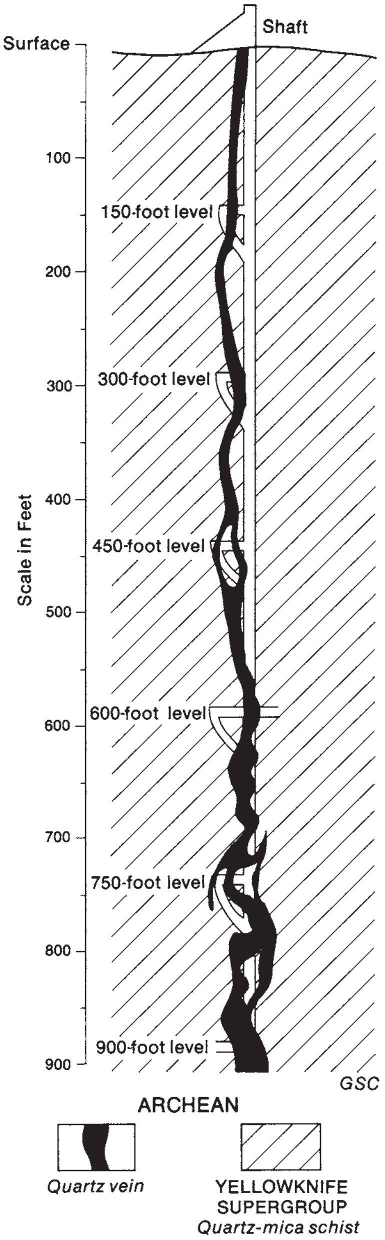


Figure 37. Vertical section through Ptarmigan shaft, Yellowknife, Northwest Territories, looking northwesterly along the strike of Ptarmigan No. 1 vein (after Boyle, 1961*a*).

enriched in biotite and chlorite. The grade of the veins was about 1 oz/ton Au.

The Cariboo Gold Quartz Mine at Wells, British Columbia (Fig. 78) obtained its ore from a myriad of quartz veins and bedded pyritic deposits in faults and fractures in the Paleozoic Cariboo series consisting mainly of quartzites, black argillites and schists (Hanson, 1935; Richards, 1948; Skerl, 1948; Sutherland Brown, 1957). Most of the quartz veins cut the sedimentary beds at large angles, but some lie nearly parallel with the strata. Their mineralization is essentially quartz with some calcite and ankerite, native gold, and small amounts of pyrite, cosalite, galena, sphalerite, galenobismutite, pyrrhotite and scheelite. The pyritic bodies are small and follow the strike and dip of the sediments. They replace limestone and limy sedimentary beds. Most consist of lenses of auriferous pyrite containing small amounts of quartz, pyrrhotite and scheelite. The average grade of the ore in the various types of deposits is 0.4 oz Au/ton. The Au/Ag ratio of the ores is about 8.

The Ordovician Meguma Group of Nova Scotia contains innumerable gold-quartz veins, some of which have been productive in the past. The Meguma Group is composed essentially of massive greywacke, quartzite, black argillite, slate and their metamorphic equivalents near Devonian granitic masses. The sedimentary rocks are folded into long pitching anticlines and synclines that yield basin and dome structures in many areas. The quartz deposits occur in the same structural locations as those mentioned for the Yellowknife Supergroup in Northwest Territories. Most of the economic deposits were saddle reefs, quartz legs and stockworks on the flanks of anticlines, or quartz masses on the limbs of anticlines in dragged and contorted slates and argillites between competent greywackes and quartzites (Figs. 40 and 41). The structural setting of the deposits has been discussed in detail by Rickard (1912), Malcolm and Faribault (1929), Newhouse (1936), Douglas (1948), Bell (1948) and Keppie (1976). The mineralization is essentially white or dark grey quartz, frequently ribboned, with small amounts of ankerite or calcite, some feldspar in places and minor to small amounts of pyrite, pyrrhotite, arsenopyrite, chalcopyrite, sphalerite and galena. Abundant stibnite is present in veins at West Gore, and molybdenite, scheelite and tourmaline occur in small amounts in a number of the deposits. Quartz veins and lenses similar to the gold veins carry small amounts of scheelite and wolframite in some areas. These are essentially barren of gold. Some of the tungsten veins appear to be younger than the gold veins. Native gold is the only economic mineral in the gold veins; gold tellurides and aurostibite have not been recognized in the deposits. Wall-rock alteration is absent to minimal in all of the deposits. The grade of the deposits ranges from 0.15 to 1 oz Au/ton or more. The fineness of the native gold spans the range 800 to 980, most samples being in excess of 900. The Au/Ag ratios of the deposits varies widely according to my analyses, from <1 to 52. Most of the ratios, however, are around 10.

Newhouse (1936) recognized a zonal arrangement of the gold deposits in Nova Scotia and related it to the granitic intrusives. Near the granitic bodies in a belt 1¼ mi wide he noted that the quartz was coarse and that the following minerals occurred in the veins with great frequency: biotite, muscovite, oligoclase, feldspar, hornblende, garnet, tourmaline, epidote, ilmenite and pyrrhotite and less frequently andalusite and molybdenite. Pyrite and arsenopyrite were universal; carbonates were rare. In an intermediate zone, 1½ mi or more from the granite contacts, carbonate and chlorite were abundant and arsenopyrite and pyrite were particularly abundant. The quartz was coarse grained but not as marked as in the zone next to the granitic bodies. In an outer zone stibnite and native antimony, as at West Gore, made their appearance. Newhouse recorded one interesting fact, the bulk of the gold was localized in the lower grade facies, that is in

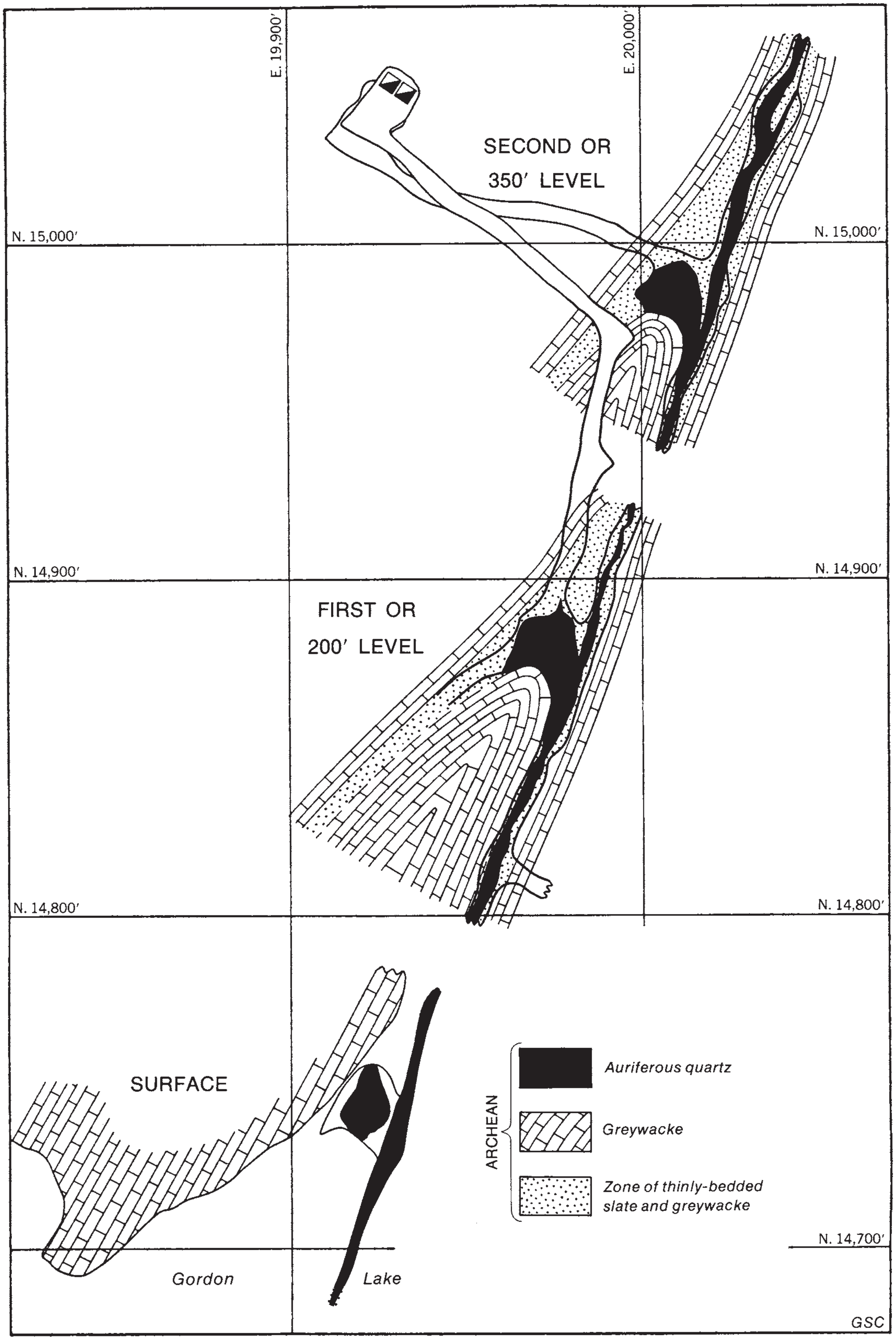
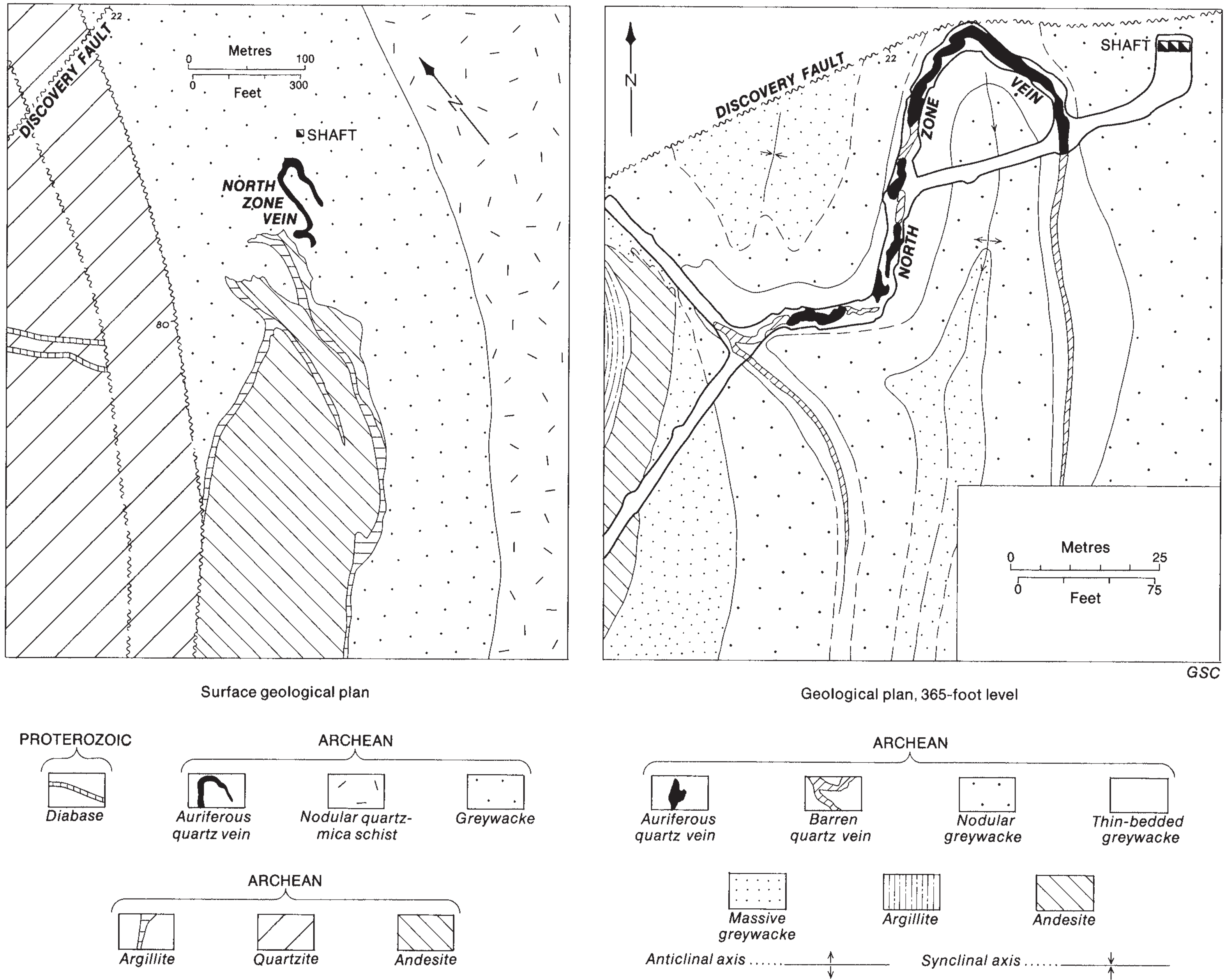


Figure 38. Plan of surface and part of underground workings, Camlaren Mine, Gordon Lake, Northwest Territories, showing geology of the Hump vein (after Henderson and Fraser, 1948).


Surface geological plan

Geological plan, 365-foot level

Figure 39. Generalized geological surface and underground plans of the Consolidated Discovery Yellowknife Mine (after Wiwchar, 1957).

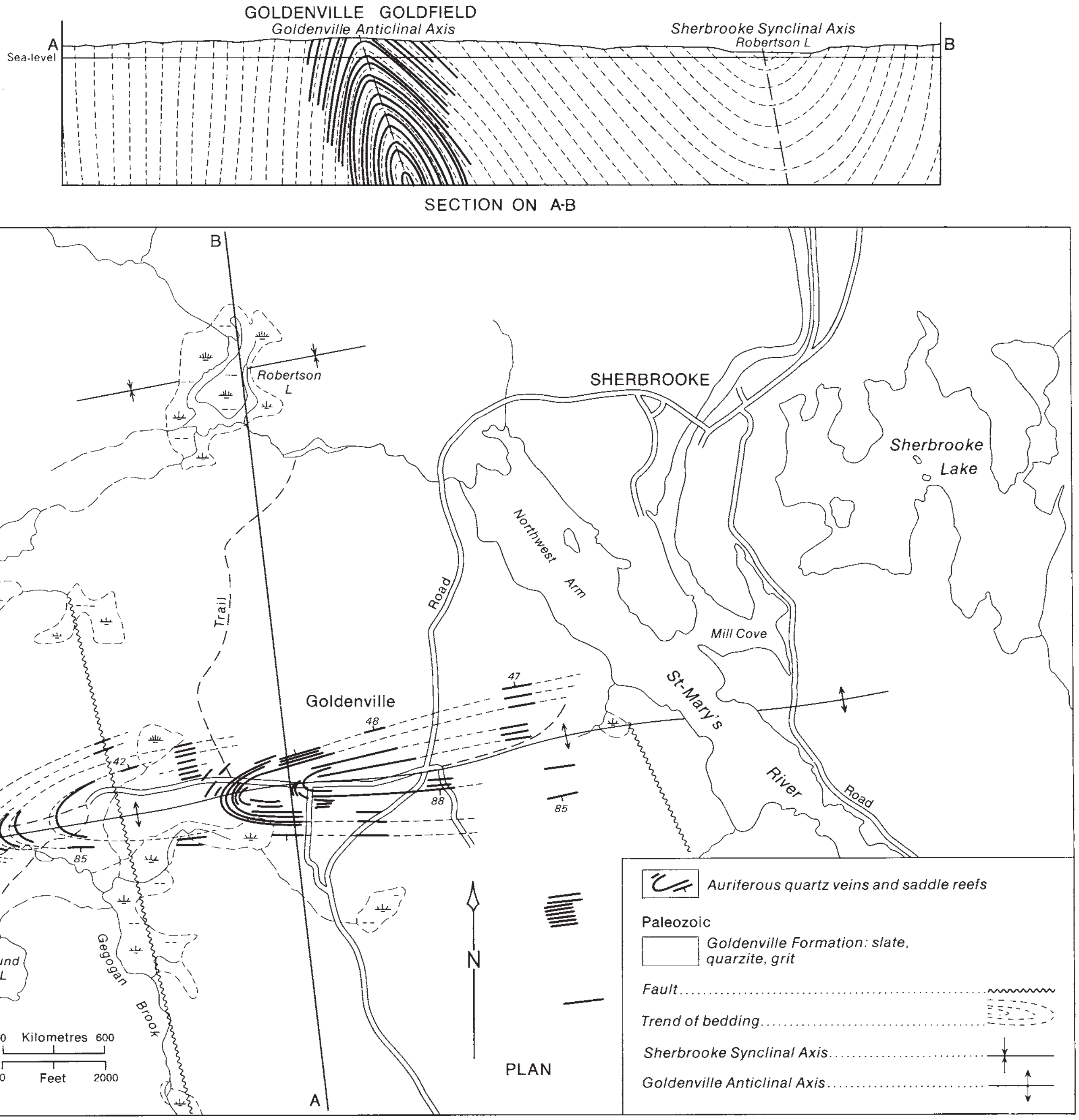


Figure 40. Generalized geological plan and section of the Goldenville gold district, Guysborough County, Nova Scotia (modified from Malcolm and Faribault, 1929).

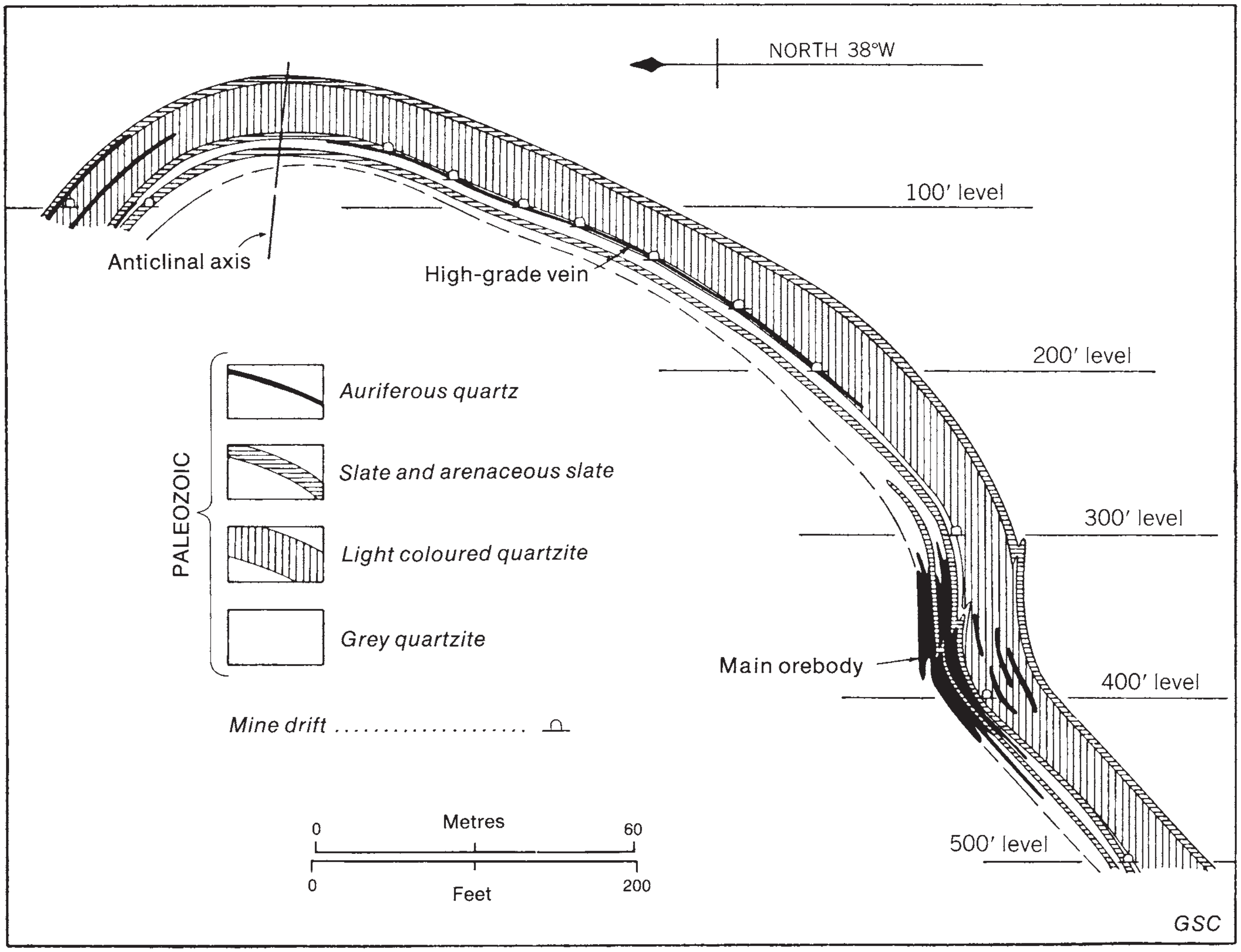


Figure 41. Vertical section through the southeastern part of the Caribou deposit, Caribou gold district, Halifax County, Nova Scotia (after Bell, 1948).

the intermediate and outer zones. Taylor and Schiller (1966), likewise, observed that most of the gold-quartz veins in the Meguma Group are confined to areas underlain by the greenschist zone of regional metamorphism. Other sedimentary gold belts in various parts of the world exhibit a similar pattern.

In the United States some of the best examples of gold deposits in sedimentary terranes include those in the Appalachian 'slate belt' that extends from Alabama, Georgia, South and North Carolina and Virginia, into Maryland (Becker, 1895; Pardee and Park, 1948; Bell, 1960). The 'slate belt' is a complex series of rocks ranging in age from Precambrian to Ordovician and including a great variety of volcaniclastic rocks, greenstones, slates, argillites, quartzites, greywackes and thin limestones here and there intruded by large and small bodies of granitic rocks of post-Devonian age (?). The deposits are varied. Some are quartz veins and lenses in shear zones, faults and fracture zones; others are conformable silicified zones in tuffaceous sedimentary rocks; and still others are replacement bodies in limestone as in the Kings Mountain area, North Carolina. The mineralization consists essentially of quartz, carbonates, tourmaline, pyrite, pyrrhotite, arsenopyrite and small amounts of galena, sphalerite, tetrahedrite, chalcopyrite, molybdenite, ferberite and scheelite. Native gold is the sole economic mineral, but gold-silver tellurides are mentioned as being present in some lodes. The grade of the ore is 0.25 oz Au/ton or less and the Au/Ag ratio of the deposits as a whole appears to average about 10 judging from the old records.

Worthington and Kiff (1970) have suggested a volcanogenic origin for the gold deposits in the slate belt of the North Carolina Piedmont. They note that many of the deposits have a spatial affinity to the Uwharrie volcanic formation, which consists of felsic pyroclastic rocks and tuffs. They envisage deposition of the deposits from hydrothermal emanations of hot springs and fumaroles associated with the waning stages of Uwharrie volcanism. Quartz vein deposits, somewhat similar to those in the Appalachians, occur in ignimbrites near Rodalquilar in southeast Spain and have been interpreted by De Roever and Lodder (1967) as related to fumarolic activity immediately following deposition of the ignimbrite.

The Salsigne Gold Mine, approximately 15 km north of

Carcassone, 90 km east of Toulouse, France obtains its ore from bodies in sedimentary rocks of Paleozoic age, folded and faulted during the Hercynian orogenic period (Reynolds, 1965; Tollon, 1970). The country rocks are limestone, dolomitic limestone, phyllite, grit and grès (phyllitic quartzite). The orebodies are sulphide bodies and quartz veins in faults mainly in phyllites, and irregular replacement bodies in dolomitic limestones and grès where intersected by faults (Fig. 42). The mineralization of the sulphide bodies consists of coarse-grained arsenopyrite, pyrite and chalcopyrite. Pyrrhotite occurs in some vein systems and minor amounts of wolframite and scheelite have been noted. The gangue is minor quartz, dolomite and siderite. The copper and silver values are relatively high, averaging 0.6 per cent Cu and 85 g Ag/ton. The gold content averages about 10 g/ton yielding an Au/Ag ratio of 0.12. The quartz veins contain essentially quartz, dolomite, siderite, chalcopyrite and minor arsenopyrite, pyrite and pyrrhotite. The grades are 12 and 28 g/ton respectively for Au and Ag yielding an Au/Ag ratio of 0.43. The mineralogy of the limestone replacements consists essen-

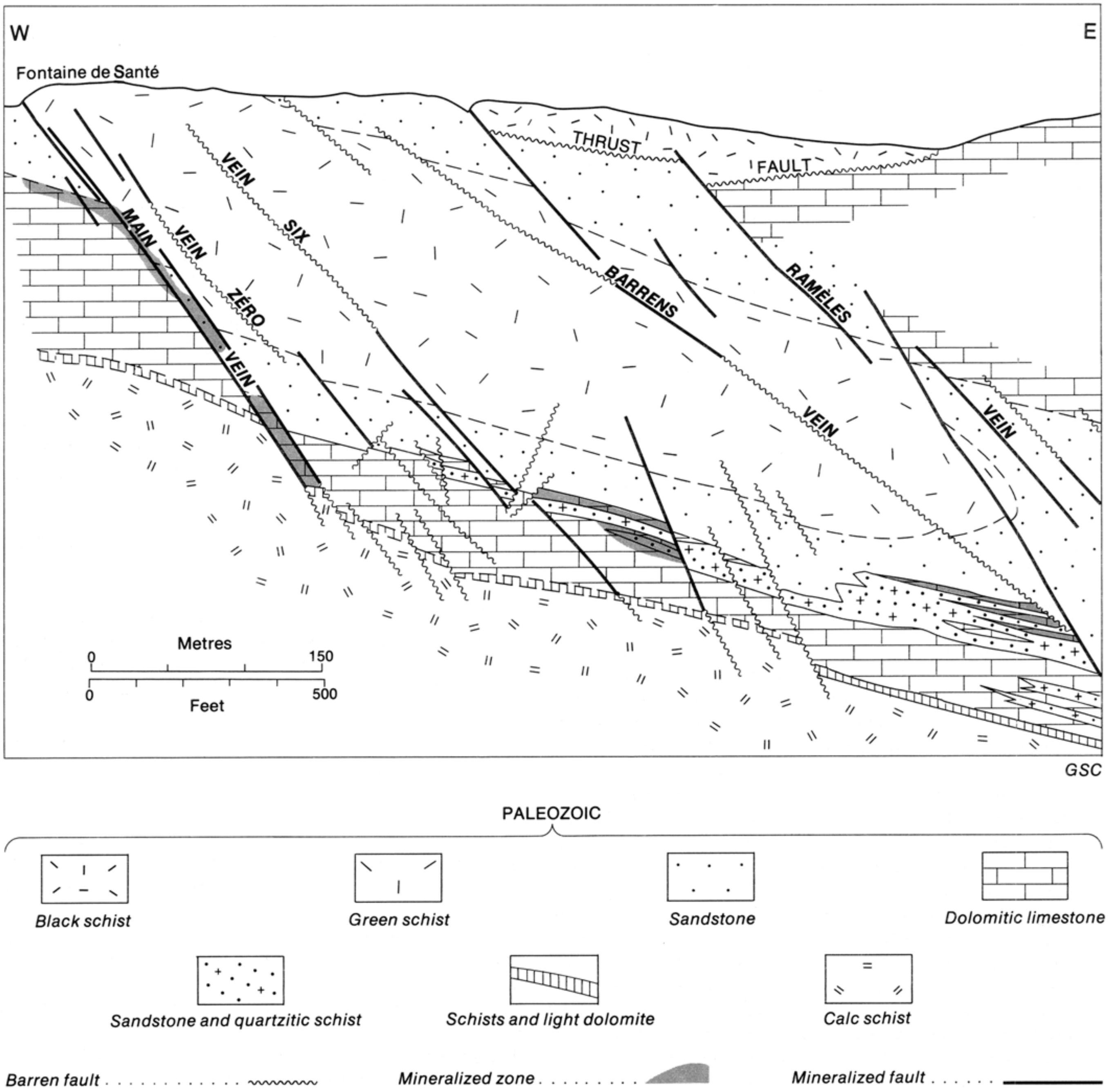


Figure 42. Generalized geological east-west section on 100 north, Salsigne Gold Mine, Montagne Noire, France (modified from Tollon, 1970).

tially of massive pyrite with much arsenopyrite and pyrrhotite, small amounts of chalcopyrite and minor amounts of galena and sphalerite. The grades are 11 g/ton Au and 25 g/ton Ag; the Au/Ag ratio, 0.44. The grès replacements are different in mineralogy and grade from the other types of ores. The mineralization consists mainly of small amounts of arsenopyrite with chlorite and quartz. Gold values may be as high as 3700 g/ton, and the bismuth contents range up to 1 per cent or more. Antimony contents are also as high as 1 per cent. The average grade of the ore is 18 g Au/ton and 10 g Ag/ton giving a Au/Ag ratio of 1.8. Wall-rock alteration effects are minimal in the deposit; in the grès replacements a little biotite is developed in the ore zones.

Tollon (1970) has recorded the presence of a large number of rarer minerals in the ores of the Salsigne Mine. These include relatively abundant bismuthinite and native bismuth, and rare pearceite, polybasite, matildite, kobellite, proustite, native silver, pyrargyrite, maldonite, cosalite, stannite, scheelite and wolframite.

The Salsigne orebodies as a whole yield gold, silver and small amounts of copper, bismuth, arsenic trioxide and sulphuric acid, the last from pyrite and pyrrhotite. In 1973 the mine produced 49 675 oz gold, 161 146 oz silver, 372 short tons copper, 41.9 short tons bismuth, 7305 short tons arsenious trioxide and 21 799 short tons of sulphuric acid (Northern Miner, Nov. 28, 1974, p. 9).

The Sovetskoe deposit described by Borodaevskaya and Rozhkov (1974) is located in the Eniseisk (Yenisey) auriferous region, which borders the Siberian platform on the west. The deposit is in Proterozoic sediments pierced by Upper Proterozoic granitoid intrusions, including granitic bodies, injection gneisses, aplite, pegmatite and diabasic porphyrite dykes. The mineralization is said to be linked with the Upper Proterozoic magmatic events. The principal stages in the geological development of the region are as follows: (1) accumulation of mainly terrigenous sediments during Lower and Middle Proterozoic time followed by carbonates in Late Proterozoic time; (2) intrusion of diabase bodies beginning during Lower Proterozoic time; (3) folding and fracturing with development of schistosity; (4) intrusion of granitic bodies accompanied by local and regional metamorphism; (5) a prolonged interval of erosion followed by the transgression of Lower Paleozoic seas and concomitant sedimentation; (6) appearance of grabens filled with Lower Paleozoic deposits and flanked by tectonic fractures that were initially activated during Upper Proterozoic time; and (7) prolonged continental conditions attended by the formation of auriferous placers in the Quaternary period (*see* Fig. 87).

The deposit is confined to uniform beds of Upper Proterozoic phyllite that has been highly sheared and drag folded, often in a complicated manner over widths of several dozens of metres and along a length of several kilometres. This shearing is related to a major thrust zone more than 10 km in extent, the ore-bearing shears being subsidiary to this so-called 'main thrust'. The orebodies are irregular and constitute stockworks of quartz veins of variable length and width that ramify hither and thither through the sheared rock. Quartz is the principal gangue mineral, and the main wall-rock alteration is tourmalinization, appearance of apatite and zircon and replacement of ilmenite by rutile; albitization, chloritization, sericitization, silicification, arsenopyritization and pyritization are marked adjacent to some of the quartz veins and stringers.

The ore minerals (about 5% of the ore) are represented by pyrite and arsenopyrite (predominant), chalcopyrite, galena, sphalerite and in places pyrrhotite and marcasite. Carbonates (calcite, ankerite), albite, sericite and chlorite are encountered among the vein minerals in addition to quartz.

The history of ore formation has been long and has included many stages. The following principal mineral associations, oldest to youngest, can be distinguished: (1) relict minerals: chlorite, muscovite, sericite, albite, ankerite, tourmaline, rutile, apatite, etc., derived from the country rocks; (2) semimilky quartz, with slight traces of muscovite and sericite; (3) arsenopyrite and pyrite; (4) polymetallic sulphide-pyrite, comb quartz, siderite, pyrrhotite, sphalerite, galena, chalcopyrite, marcasite and very rarely, bismuthinite, native silver, freibergite, maucherite and violarite; (5) gold with a small quantity of calaverite; and (6) carbonates and collomorphic pyrite. N. Petrovskaya (*in* Borodaerskaya and Rozhkov, 1974) has suggested that the main body of vein quartz was probably deposited from highly concentrated hot silicate solutions and has further demonstrated that the quartz underwent intensive metamorphism and recrystallisation before the mineral associations next in age were deposited.

The mineral associations enumerated above are unevenly distributed in the various bodies, with the result that the following ore types can be distinguished: homogeneous quartz ores, quartz ores with relicts from the surrounding shales, quartz-pyrite ores (with impregnated or pockety mineralization) and quartz-arsenopyrite and quartz-sulphide ores mixed with traces of the polymetallic sulphide group. The latter ore type has the highest gold content. The orebodies near the walls of the sheared zones, where breccia structures predominate, are the richest; the poorest are in the inner parts of the sheared zones; these are composed of massive, low sulphide-bearing quartz.

The gold in the ores is present mainly in the native form as small angular, fibrous and nodular forms, the grains ranging from 1μ to several millimetres in cross-section. The fineness of the native gold is rarely less than 850. The purest gold comes from quartz ores low in sulphides; in the polymetallic sulphide ores the gold contains traces of zinc, lead and copper; traces of selenium and tellurium are also noted in some samples.

The Sovetskoe deposit is a large tonnage proposition; it resembles in many respects the low grade Alaska Juneau deposit at Juneau described in the next section. The grade of the Sovetskoe deposit is not given, but it probably averages about 0.1 oz/ton.

The Muruntau deposit in Uzbec S.S.R. is an en echelon system of thick steeply dipping auriferous quartz veins, intersected by stockworks of gently dipping gold-bearing quartz and quartz-sulphide stringers and veins (Fig. 43). The host rocks are Paleozoic calcareous siltstones, shales and various types of schists. The geology and mineralization of this deposit is discussed in detail by Nesterova and Chebotarev (1969), Yudin (1971), Borodaevskaya and Rozhkov (1974) and Baimukhamedov *et al.* (1975*b*).

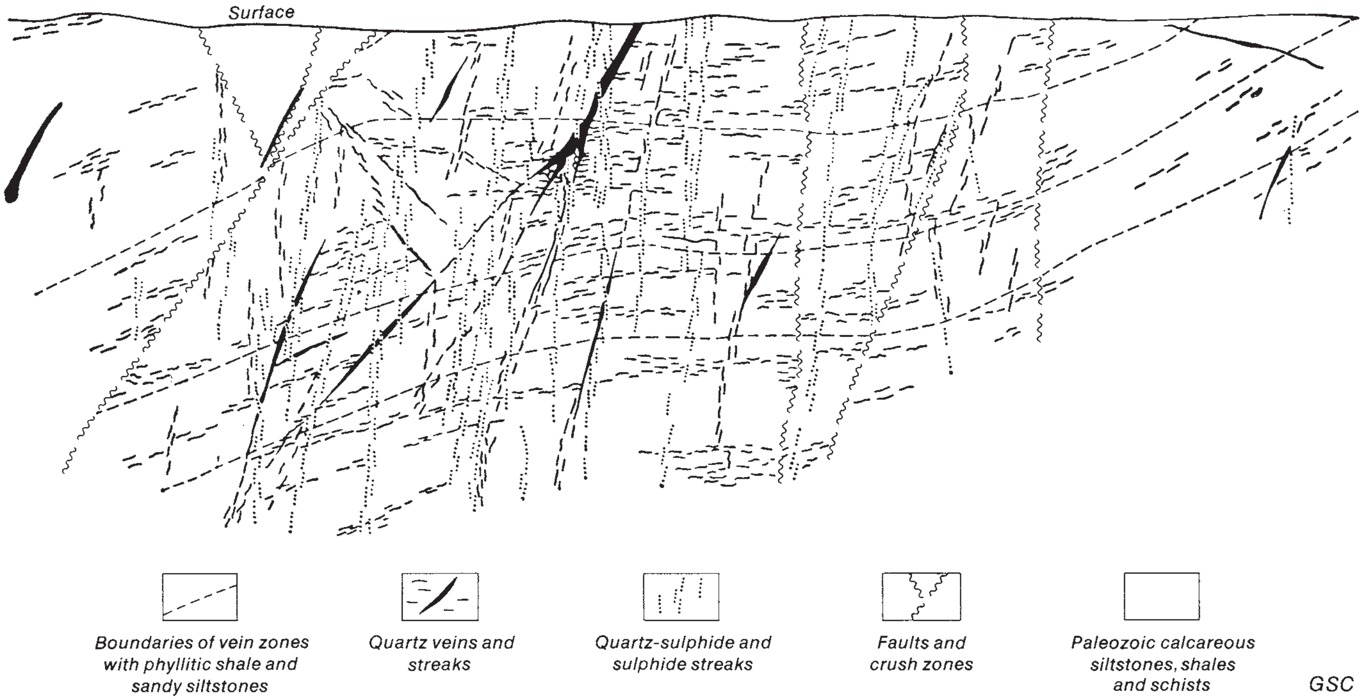


Figure 43. Geological section of the Muruntau gold deposit, Uzbec S.S.R. showing the interrelationship of gently and steeply dipping vein zones (after S. Sher, *in* Borodaevskaya and Rozhkov, 1974). (No scale given on original.)

Three stages of alteration and mineralization are recognized as follows: preore, ore and postore.

The preore stage includes three phases. The early mineral associations related to the metasomatic alteration of the wall rocks originated during the first phase. The new minerals formed were pyroxene, actinolite, feldspars, chlorite, biotite, sericite, graphite, ferruginous tourmaline (schorl) and pyrrhotite, all of which originated mainly as the result of the rearrangement of the components of the wall rocks. These minerals jointly with metasomatic quartz are distributed in the shales as accumulations along the bedding planes, as lenticular stringers, or as 'shadows' associated with quartz grains. The second phase, closely related to the first, produced a system of concordant and discordant veins and stringers filled with coarse-grained quartz, the constant associates of which are orthoclase, scheelite and wolframite. The third phase is represented by monomineralic veins of coarsely-crystalline columnar quartz.

The ore stage began with the intrusion of dykes of diverse composition. Next followed the formation of latitudinal fractures, brecciation of the coarse-grained quartz veins and stringers formed during the second phase of the preore stage and deposition of minerals of the second stage of the mineralization. This stage comprises four phases of mineral deposition. During the first phase quartz-albite metasomatites were superimposed upon the altered zones formed during the preore stage. The second phase of mineralization was repeatedly interrupted by fracturing during which some quartz-arsenopyrite-pyrite stringers were deposited first, followed by the main period of pyrite-arsenopyrite mineralization. Chalcedony and rosettelike quartz aggregates were deposited during the third phase, which was followed by the fourth or the main quartz-gold-polymetallic phase of ore deposition. This phase resulted in the deposition of two distinct associations of minerals, an early generation including pyrrhotite, molybdenite, pyrite, sphalerite, galena, chalcocite and tetrahedrite, and a late one marked by native gold, native bismuth, bismuthinite, gold tellurides (?), altaite and miargyrite.

The initiation of the postore stage was characterized by the precipitation of a peculiar quartz-tourmaline-pyrite association, localized on the whole in lenslike bodies of quartz-tourmaline breccia. Next followed the deposition of veins of columnar quartz with small amounts of pyrite and calcite. The last minerals formed were carbonates, represented mainly by calcite and subordinated by dolomite stringers oriented at random and intersecting all earlier stages of mineralization.

In a recent contribution on the geochemistry of the Muruntau gold deposit Petrov (1972) states that the ore is localized in quartz and quartz-mica schists containing lenticular lenses of limestones. The schists are said to be enriched in gold (100–1000 ppm), As (<100 ppm), W (<1000 ppm), Bi (10 ppm), Cu (4–10 ppm), Zn (2–3 ppm) and Co (1.5–2 ppm). He proposes a syngenetic origin for the deposit.

The grade of the Muruntau deposit is not stated in most publications. The fineness of the native gold ranges from 737 to 953 with an average of 889. In a recent report by Bendik and Nesterova (1971) the grade is given as 0.058 oz Au/ton (2 ppm) and 2.9 to 8.8 oz Ag/ton (100–300 ppm). The gold content stated seems low considering the values quoted by Petrov above. Baimukhamedov *et al.* (1975*b*) give the grade of the metasomatites as 0.5 to 3.5 g/ton Au.

The rich hypogene gold deposits of Victoria, Australia, now largely exhausted, are mainly in Lower Ordovician sedimentary sequences composed essentially of slate, argillite, greywacke, grit and quartzite intruded in places by Devonian granitic masses (Thomas, 1953; various papers in Edwards, 1953; McAndrew, 1965; Woodall, 1975; Bowen and Whiting, *in* Knight, 1975). The chief gold mining centres were Bendigo and Ballarat, about 80 mi northwest of Melbourne and Castlemaine, Clunes, Berringa, Scarsdale, Daylesford and Maldon. The sedimentary rocks are closely folded into series of pitching anticlines and synclines giving dome and canoe structures. The gold deposits are mainly quartz bodies along bedding planes, in faults cutting the sedimentary beds at a high angle and in saddle reefs on anticlines and trough reefs in synclines. Some saddle reefs are stacked and have well-developed spurs as shown in Figure 44. The Bendigo and Ballarat fields are well-known for their classic saddle reefs, and these two fields have been the most productive. The mineralization in the saddle reefs and other deposits is essentially coarse-grained quartz, some feldspar (albite), dolomite, ankerite or calcite, chlorite, pyrite, arsenopyrite, rarely pyrrhotite, galena, chalcopyrite, sphalerite, and locally molybdenite, bismuth, stibnite, bournonite and other sulphosalts. The only economic minerals are gold and stibnite. Arsenic has been recovered as a byproduct from some of the gold deposits. The native gold usually averages about 850 fine. The grade of the deposits ranged from 0.4 to 0.9 oz Au/ton.

The Telfer Mine developed by Newmont Pty. Ltd. is in the Paterson Range of Western Australia and comprises quartz and quartz-limonite reefs with pyrite boxworks and free gold mainly concordant with, but locally cutting at a small angle, a sequence of metamorphosed stable shelf sediments including sandstone, siltstone, shale and dolomite correlated with the Middle Proterozoic Bangemall Group (Blockley, 1974). Granite dated at 600 m.y. intrudes the sediments some 15.5 mi west of the deposits. Most of the auriferous quartz deposits occur in domes or anticlines, and many are saddle reefs. The average grade of the limonitic deposits (oxidized surface parts) is about 0.5 oz/ton Au. At depth in the primary zone the quartz contains mainly pyrite and gold, and the average grade is lower. Auriferous gossans mark many of the deposits.

The Reefton goldfield, the most productive of the gold deposits in Precambrian(?) rocks in the northwestern part of South Island, New Zealand, occurred in an extensive set of narrow, steeply dipping crushed zones, shears and small faults developed near the axes of folds in Waiuta Group greywackes, argillites and phyllites (Henderson, 1917; Gage, 1948; Williams, 1974). The lodes in the Blackwater Mine, the principal producer, were a series of quartz veins and stringers in crushed rock and clay. The mineralization was essentially quartz, minor carbonates, pyrite, arsenopyrite, stibnite, minor chalcopyrite, galena, minor silver and molybdenite. The average grade was about 0.5 oz Au/ton. Some 80 per cent of the gold was free though rarely visible. Secondary enrichment was unimportant.

The gold deposits of South Africa appear to belong to three metallogenic periods. These include an early Precambrian (Archean) period in which most of the deposits are in or associated with greenstones of volcanic origin in the Swaziland System; a later Archean or early Proterozoic period when the great deposits of the Witwatersrand were formed; and a late Precambrian period wherein the deposits appear to be

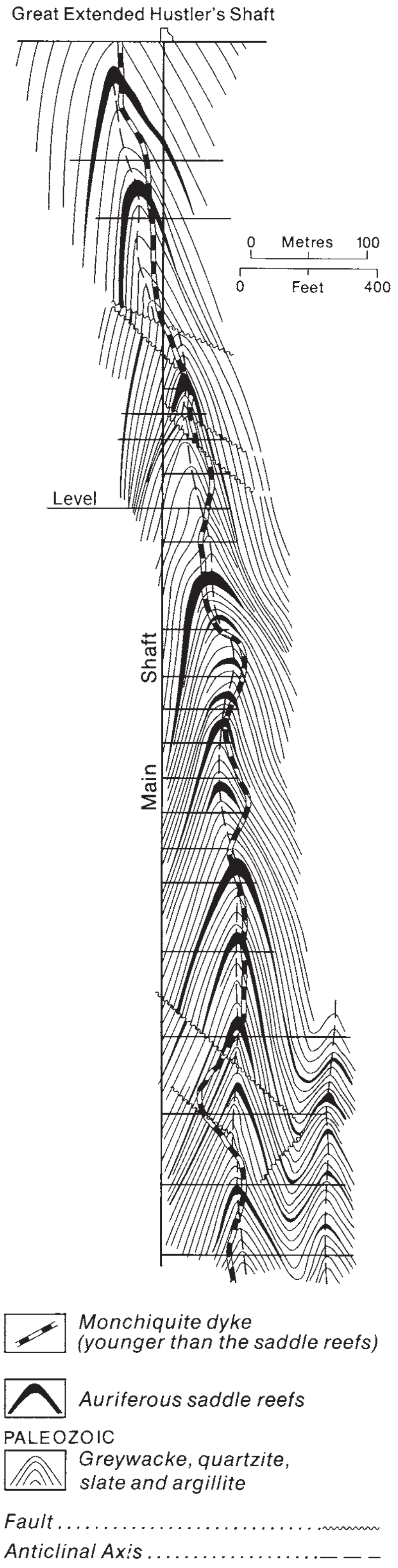


Figure 44. Stacked saddle reefs, Bendigo goldfield, Victoria, Australia (modified from Herman, 1914).

related to granitic and other rocks of the Bushweld Complex. The last period is marked by important deposits in the Pilgrim's Rest and Sabie districts. Most of these deposits are in sediments (Reinecke and Stein, 1930; Wybergh, 1930; Geol. Surv. S. Afr., 1959; Pelletier, 1964).

The gold deposits of the Pilgrim's Rest and Sabie goldfields lie mainly in the Dolomite and Black Reef series of the Transvaal System (*see* also Table 61). The Black Reef Series, composed essentially of sandstone and conglomerate, lies directly on the older gneiss, schist and granite (Swaziland System) and is followed upward by the Dolomite Series, which is essentially constituted of thick beds of dolomite with thin shale beds and bands of chert. Lying on top of the Dolomite Series is the Pretoria Series consisting of shales and interbedded quartzites. This series contains a few small gold deposits. The sedimentary beds are penetrated by a number of granitic, dioritic and gabbroic sills, stocks and dikes. The gold mineralization cuts these igneous bodies in places.

The more important deposits (reefs) are the Theta, Beta, Portugese, Vaalhoek and Glynn's reefs in the Dolomite Series and the Sandstone Reef in the Black Reef Series. These are mainly bedding plane quartz veins generally 1 to 3 ft or more thick. Cross-cutting quartz veins that join the bedding plane veins occur in some deposits, and a 'Blow' occurring just below Glynn's Reef in the Elandsdrift Mine near Sabie consisted of a steeply dipping fragmented pipelike mass containing pieces of dolomite, chert, shale and quartz cemented by quartz and pyrite. The mineralization in all of the deposits consisted mainly of quartz, both fine-grained laminated and coarse-grained massive, carbonates, chalcopyrite, arsenopyrite, sphalerite, galena, bismuthinite, considerable amounts of pyrite, frequently in massive layers in some reefs and native gold. The gold was commonly finely divided and invisible to the eye. The grade of the deposits ranged from 0.35 to 0.75 oz Au/ton.

Gold-silver and silver-gold veins, lodes, stockworks and silicified zones in a complex geological environment, comprising sediments, volcanics and various igneous intrusive and granitized rocks

Deposits in this category combine nearly all the epigenetic features described for the previous categories. The origin of their metallic and other components may lie in the combined group or groups of rocks in which they lie, particularly interbedded sedimentary and volcanic piles. The deposits are best illustrated by specific examples. Those chosen include the Alaska Juneau Mine at Juneau Alaska; Grass Valley, California; the Rossland gold-copper belt in British Columbia; the Little Long Lac–Sturgeon River district, Ontario; the Renabie Mine in Leeson Township, Ontario; the Kirkland Lake district, Ontario; and the Central City district, Colorado. There are hundreds of other deposits throughout the world that have similar features.

Most of the deposits in this category are mainly quartz veins or lodes, stockworks or silicified zones in faults, fractures, shear zones, sheeted zones and breccia zones. Many of the deposits occur in volcanic rocks and pass into intruding granitic bodies indicating that they are later than the major periods of granitization and igneous injection. Other deposits occur in sediments, their metamorphic equivalents and in the associated granitized zones or intruded granitic rocks. As in the volcanic terranes the deposits are later than the granitization and granitic injection periods.

Some deposits are in rocks as old as Precambrian but were deposited during Tertiary time. The Central City district is a good example of this phenomenon. There are many other examples of younger deposits in much older host rocks in U.S.S.R., Japan and elsewhere.

The Alaska Juneau Gold Mine, now exhausted, was well known for its large tonnage mining operation (10 000 tons/day) and gold production from gold orebodies averaging 0.04 oz Au/ton. The orebodies (Fig. 45) were localized in an extensive stockwork of quartz veins and stringers, some 1000 to 2000 ft wide, 3½ mi long and extending downward at least 3000 ft, ramifying through a belt of contorted and altered greenstone, sills and dykes of gabbro, slate, tuffs and schists of Mesozoic age (Wernecke, 1932). The stockwork zone was extensively altered, biotitization, sericitization and silicification being the principal processes. The mineralization consisted essentially of quartz, albite, ankerite, calcite, pyrite, galena, pyrrhotite, chalcopyrite, sphalerite and native gold. The gold grade averaged about 0.04 oz/ton; the silver values were low.

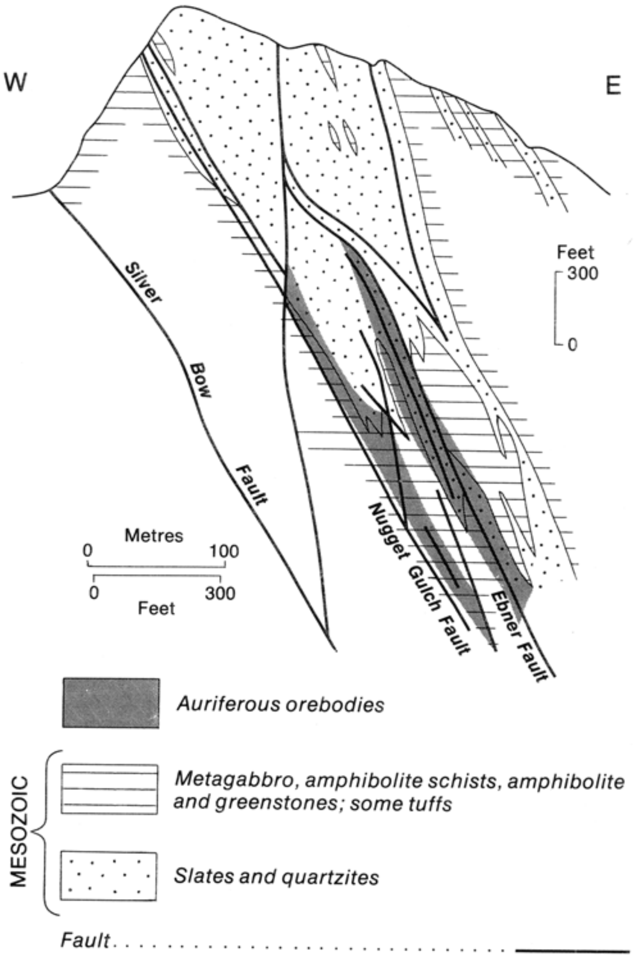


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Figure 45. Typical cross-section, Alaska Juneau Gold Mine, Juneau, Alaska (after Wernecke, 1932).

The Grass Valley gold district and the Nevada City deposits some 4 mi apart formed one of the greatest lode-gold centres in east central California. The deposits are described in some detail by Lindgren (1896), Howe (1924), Farmin (1938), Johnston (1940) and Clark (1970). The deposits are persistent quartz veins and lodes and quartz stockworks and sheeted zones developed in faults, fractured zones and brecciated zones that cut Paleozoic and Mesozoic amphibolites (greenstones), slates, schists, etc. intruded by a granodiorite pluton of Mesozoic age. The deposits occur in all rock types, and the wall rocks are strongly sericitized and carbonated and moderately chloritized, epidotized, pyritized and arsenopyritized. The mineralization is essentially ribboned quartz, with variable amounts of ankerite and calcite, pyrite, arsenopyrite, galena, sphalerite, tetrahedrite, chalcopyrite, molybdenite, minor pyrargyrite, some scheelite, gold and small quantities of various tellurides. The grade averaged about 0.5 oz Au/ton, and the Au/Ag ratio of the ores was about 3.7. Johnston (1940) thought that the quartz veins grew by accretion from aqueous solutions; Farmin (1938, 1941) on the other hand considered that the veins were intruded as a highly concentrated magmatic solution of quartz (vein-dykes).

The Rossland gold-copper camp in the West Kootenay district of British Columbia produced during its lifetime some 6 200 000 tons of ore averaging 0.47 oz Au/ton, 0.6 oz Ag/ton and 1 per cent Cu from veins in a complex geological environment (Drysdale, 1915; Gilbert, 1948; Little, 1960; Thorpe, 1967).

The country rocks in the Rossland camp are interbedded greenstone flows, sills and sediments (Rossland volcanics) of Lower Jurassic age, all cut by a succession of offshoots or satellites of the Nelson batholith, including monzonite, granodiorite, alkaline syenite, pulaskite, granite, granite porphyry and lamprophyre. The orebodies were replacements along fissures chiefly in augite porphyry and monzonite. The mineralization consisted essentially of pyrrhotite, chalcopyrite, some pyrite and arsenopyrite, small amounts of gersdorffite, galena, sphalerite, stibnite, bismuthinite, molybdenite and marcasite, in a gangue of altered wall rock containing variable amounts of quartz and calcite. The alteration consisted of the development of minerals such as wollastonite, actinolite, garnet, epidote, prehnite, laumontite, chabazite, tourmaline, apophyllite, muscovite, biotite, chlorite and serpentine. Many of the veins were nearly massive sulphides; others were composed of disseminated sulphides. Some of the gold was free, and some was combined as telluride; a large part of the gold is present in chalcopyrite, pyrite, arsenopyrite and other sulphides as a finely divided or submicroscopic (lattice?) constituent. There was a close association between bismuthinite and gold in some stopes, and between molybdenite and gold in others. In most samples the gold is a late mineral in the paragenesis, impregnating arsenopyrite, bismuthinite, molybdenite and other sulphides.

Fyles *et al.* (1973) claim on the basis of K-Ar data that the mineralization at Rossland is of Tertiary age, but Thorpe and Little (1973) caution against accepting this age until U-Pb dating of zircon and whole-rock Rb-Sr dating are done.

The Little Long Lac–Sturgeon River gold district centred on Geraldton, Ontario had five major producing mines (Leitch, Northern Empire, Jellicoe, Bankfield and Tombill, and Hard Rock). The country rocks of the district are Archean (Keewatin) volcanics overlain unconformably by (Timiskaming) sediments and cut by diorite, feldspar porphyry and granodiorite (Horwood, 1948*a*; Pye, 1952). Most of the deposits are quartz veins and lodes in shear zones, drag folds, fracture zones and faults in folded greywacke, slate and iron-formation in the (Timiskaming) sediments. Other deposits are quartz veins and lodes similarly structurally located in Keewatin greenstones and their associated interbedded pyritiferous slates, tuffs and iron-formation. A few veins are in quartz porphyry, diorite and granodiorite. The mineralization was quartz with small amounts of pyrite, pyrrhotite, arsenopyrite, chalcopyrite, stibnite, tetrahedrite, other sulphosalts, tourmaline and native gold in most of the deposits in the sediments. In the deposits in the greenstones ankerite was common. Some of the gold-bearing bodies in iron-formation in the Hard Rock Mine were nearly massive pyrite and arsenopyrite with pyrrhotite in places (Matheson and Douglas, 1948). Alteration in the sediments was minimal; in the greenstones and porphyries carbonatization and sericitization predominate. The grade of the orebodies ranged from 0.3 to 0.5 oz Au/ton and the Au/Ag ratio of the ores was about 8 to 10.

In the Northern Empire Mine in the Little Long Lac district a thick, flat diabase sill cut out some 500 ft of the vein (Fig. 46). On the upward and downward extension of the vein for some 50 ft or more from the diabase the gold was extensively leached from the vein (Benedict and Titcomb, 1948). This mobilization and rearrangement of gold is common where late igneous bodies cut through gold-quartz deposits. At Yellowknife the late diabase dykes commonly become enriched in gold in the vicinity of the gold ore shoots; in other cases gold is concentrated in the orebodies adjacent to the diabase. In this case, as opposed to the situation at the Northern Empire Mine, the diffusion was, apparently toward the hot source, not away from it as one might expect on a cursory examination of the phenomenon. In the Rand of South Africa where igneous bodies cut through the gold-bearing bankets both enrichments and impoverishments of gold near dykes and sills have been noted (*see* page 324).

The Renabie Mine in Leeson Township, Ontario developed orebodies mainly in granite and tonalite gneiss and massive granite that intrudes andesitic lavas (greenstones) of Archean age (Bruce 1944, 1948; Rice, 1949). Four bodies of gold-bearing quartz were exploited including a pipe-shaped mass and three zones of quartz lenses and stockworks. Most of the quartz in the four orebodies is a granular white variety with brownish streaks, cut by veins of a younger white quartz. Only small amounts of metallic minerals occur in the older quartz and practically none in the younger. Pyrite is the most abundant sulphide; galena is sparingly present and erratically distributed. The native gold is microscopic in character; it is associated with carbonaceous substances (graphite) in some of the veins. The grade of the ore averages 0.2 oz Au/ton and the Au/Ag ratio is 2.7.

The Kirkland Lake gold belt in northern Ontario during its heyday boasted 10 major gold producers – Amalgamated Kirkland, Macassa, Kirkland Lake Gold, Teck Hughes, Lake Shore, Wright Hargreaves, Sylvanite, Toburn, Bidgood Kirkland and Upper Canada. After more than 50 years of mining

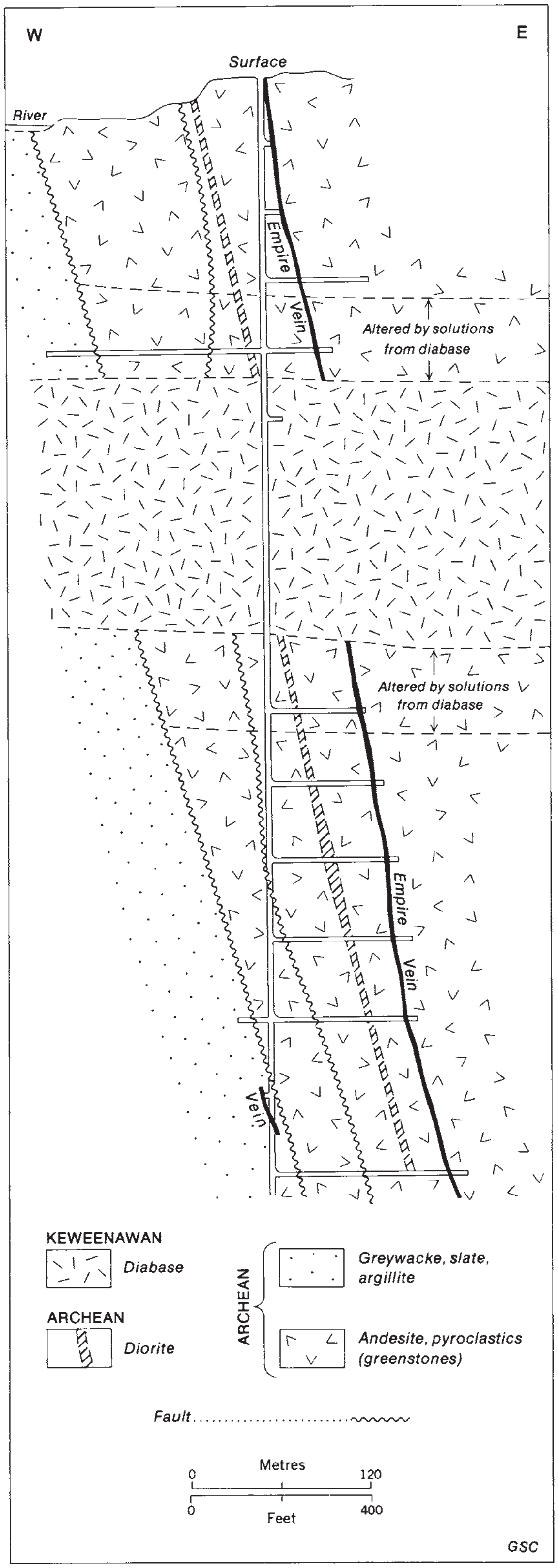

Figure 46. Vertical cross-section through shaft, Northern Empire Mine, Beardmore, Ontario (after Benedict and Titcomb, 1948).

most of the orebodies of these mines are now exhausted. The country rocks are steeply folded Precambrian sediments, including conglomerate, greywacke, slate, iron-formation, trachyte flows and tuffs lying in an east-west synclinal structure the flanks of which are marked both north and south by Keewatin greenstones and their associated tuffs and iron-formations. The greenstones and sediments are intruded by granodiorite, syenite and syenite porphyry, the last, one of the most favorable for ore shoots at Kirkland Lake. The structure and mineralization of the Kirkland Lake gold belt is described in great detail by Thomson *et al.* (1950).

Most of the gold deposits in the Kirkland Lake gold belt are in a thrust fault locally called the 'main break' or the Kirkland Lake Fault, which cuts through the sedimentary rocks and syenite and syenite porphyry plugs invading them (Fig. 47). Associated with the 'main break' are a number of bifurcating and parallel faults, all heavily mineralized in places. The orebodies were mainly fissure veins, but some were stockworks, breccia veins and gash veins. All were cross-faulted by postore movements. The principal gangue was quartz, but in some veins the mineral was relatively sparse, the oreshoots being silicified, mineralized mylonite along the fault. Other gangue minerals in small amount were calcite, albite, orthoclase, ankerite, barite, tourmaline, actinolite and minor apatite. The metallic minerals were mainly pyrite, chalcopyrite, galena, sphalerite, molybdenite, hematite, graphite, native gold and a number of tellurides, including altaite, coloradoite, calaverite, petzite and melonite. The grade of the ores was about 0.5 oz Au/ton and the average Au/Ag ratio of the deposits as a whole ranged from 4 to 9. The fineness of the native gold averaged about 940 and that of the bullion about 860. As Hopkins (1950) has pointed out this means that some 9 per cent of the silver in the bullion must have come from sources other than native gold. Some of the excess silver was provided by some of the tellurides, some by galena, but the bulk probably by pyrite in which silver tends to exceed gold in content according to the writer's analyses. This appears to be normal in a number of gold mines in Precambrian rocks.

The Central City district, Colorado, some 30 mi west of Denver, is of great interest as a gold-bearing province since the mineralization is of Tertiary age whereas the host rocks are mainly Precambrian. The geology of the district has been investigated in great detail and is described by Lovering and Goddard (1950) and Sims *et al.* (1963).

The Central City district is part of a larger zoned belt of mineralization that transects the grain of the Front Range at a small angle, stretching northeast from Breckenridge to Jamestown (*see* insert in Fig. 48). The Central City district is underlain mainly by Precambrian rocks comprising sedimentary gneisses and schists, migmatites, pegmatitic masses and a granodiorite body. The only younger rocks are a variety of Tertiary porphyries (Fig. 48).

The mineral deposits are mainly veins and lodes localized in a great anastomosing series of fractures and small faults that trend northeast and generally dip more than 60°. There is also a large oval stockwork (The Patch) that is believed to be a mineralized pipe of explosion breccia. All of the veins are younger than the Tertiary dykes and irregular bodies. Most veins and the stockworks contain essentially quartz, minor

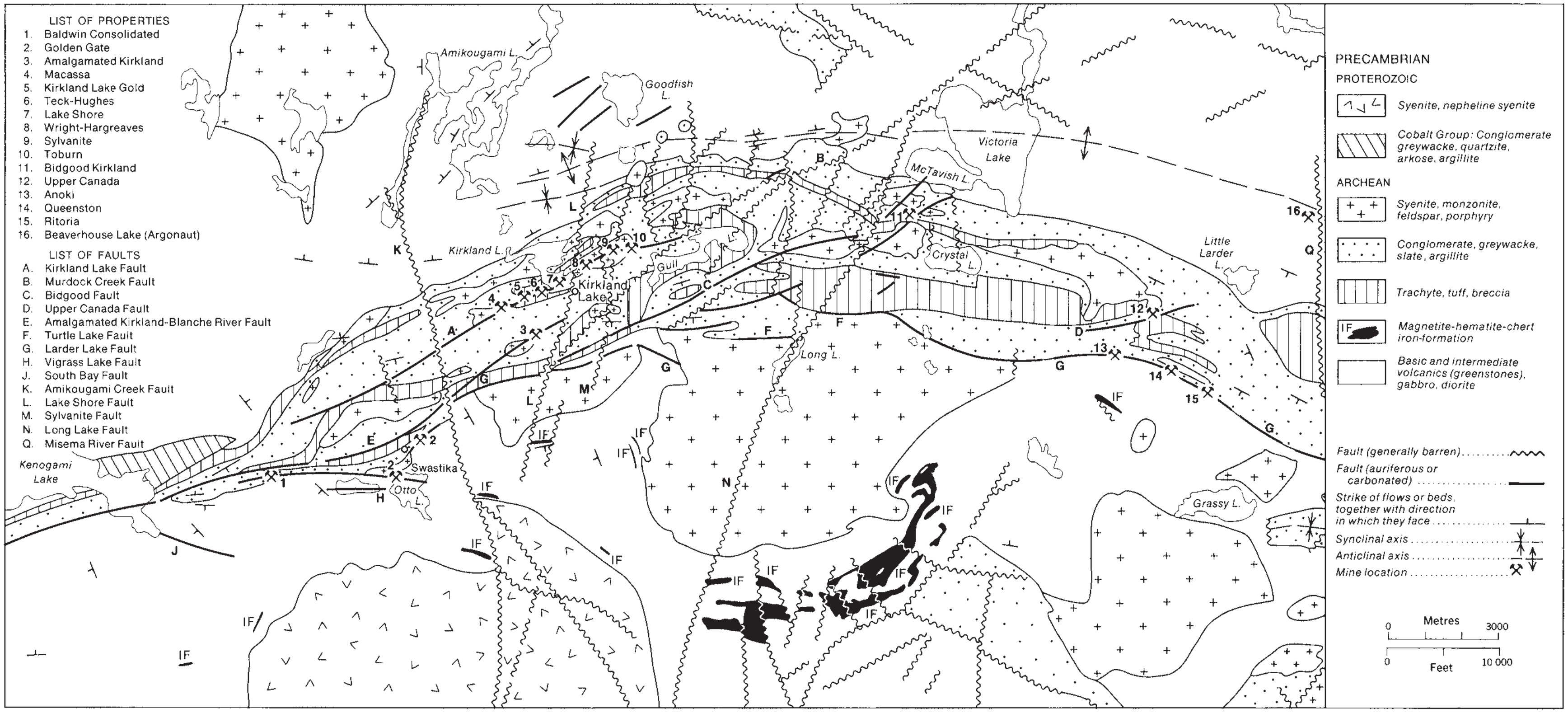

Figure 47. Generalized geological map showing the setting of the Kirkland Lake gold deposits (after Thomson, 1950).

Contents

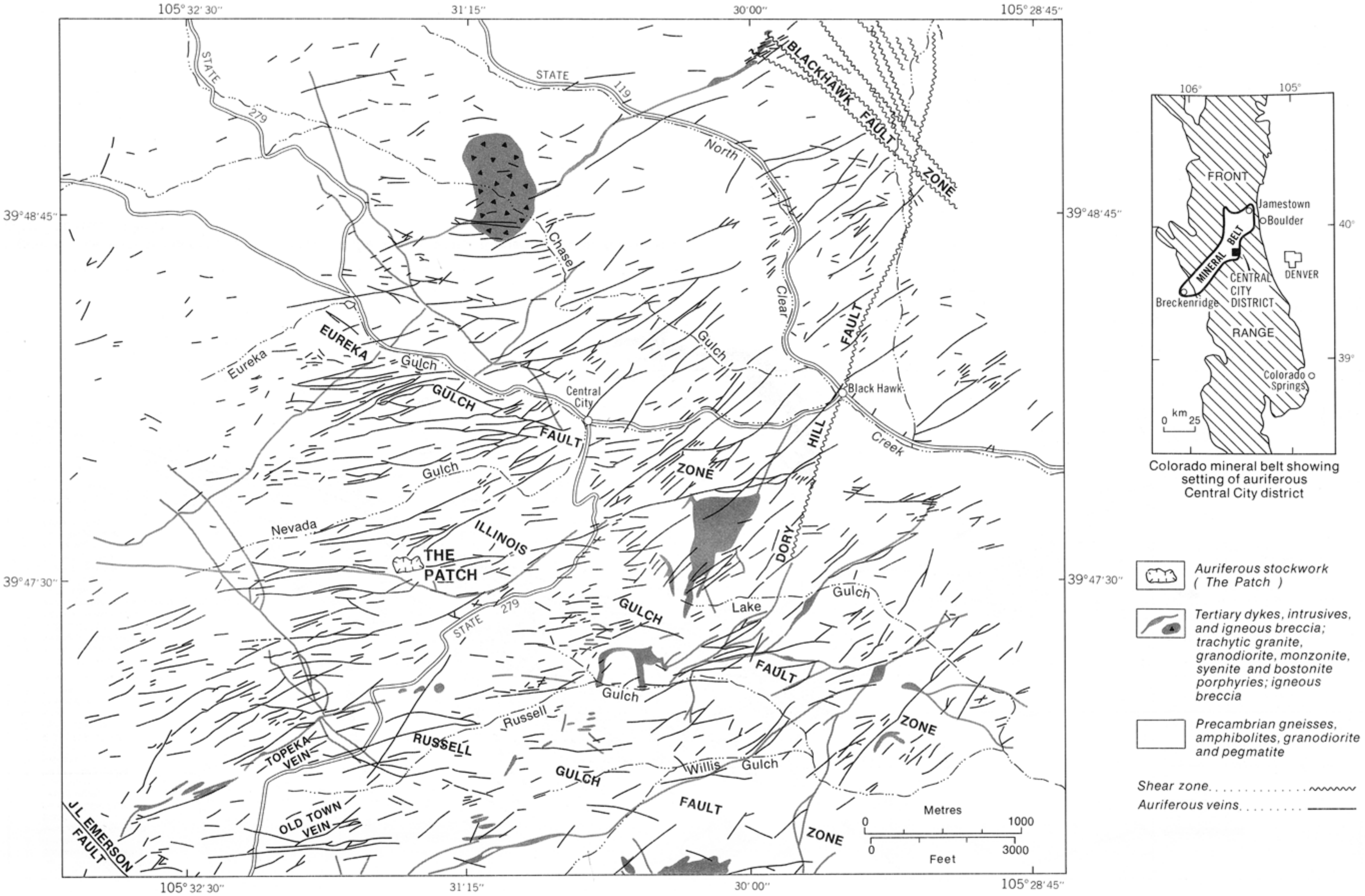

Figure 48. Generalized geological setting of the gold and other veins of the Central City district, Colorado (after Sims *et al.*, 1963).

fluorite, pyrite, sphalerite, chalcopyrite, tetrahedrite-tennantite, galena, native gold, and small amounts of bismuth, molybdenite, enargite, ruby silver, ferberite and Au-Ag tellurides. Pitchblende is a local constituent of some veins and has been mined as an ore mineral. The average grade of the smelting ore from the pyrite veins was 1.78 and 5.9 oz/ton of gold and silver respectively. The Au/Ag ratios of these veins ranged from 0.065 to 0.62. The average grade of the galena-sphalerite veins was 0.39 and 40.18 oz/ton of gold and silver respectively. The Au/Ag ratios ranged from 0.008 to 0.08. The highest silver concentrations were associated with galena and copper minerals. Pyrite in all types of deposits contained low contents of silver as did also most samples of sphalerite. Much of the gold was associated with chalcopyrite and tennantite, and less so with pyrite, galena and sphalerite.

According to Sims *et al.* (1963) the veins are distributed according to a well-defined, concentric zonal arrangement. A core of pyrite veins (central zone) is surrounded by a peripheral zone of galena-sphalerite veins; an intermediate zone contains transitional veins that consist of the minerals characteristic of both the central and peripheral zones. Most of the important mines are in the intermediate zone.

Sims *et al.* (1963) also state that although the veins were formed during a single period of mineralization, the major vein minerals were deposited in three stages, from oldest to youngest – a uranium, a pyrite and a base metal stage. The pyrite and base metal stages of mineralization were of broad areal extent and produced the district-wide zoning, whereas the uranium-stage mineralization was of local extent.

The ores were formed during the Laramide orogeny and were, according to Sims *et al.* (1963), derived from the magmas that consolidated to form the porphyries of the district. Lead-uranium isotope ages of uraninite from the veins indicate an absolute age of mineralization of about 60 m.y.

At the northeast extremity of the Colorado mineral belt, in the Jamestown, Gold Hill and Magnolia mining districts of Boulder County, there are a large number of gold telluride deposits that have been extensively mined in the past. These are described in detail by Kelly and Goddard (1969).

The predominant country rocks are Precambrian granites, gneisses and schists intruded here and there by various Tertiary intrusives mainly of biotite latite. The veins are of Early Tertiary age and are composed essentially of an interlacing network of pyritic or marcasitic horn quartz in which the ore minerals are sparse and irregularly distributed. The chief ore minerals are sylvanite, petzite, hessite, calverite, krennerite and native gold. Native tellurium and a variety of tellurides also occur. The gangue minerals are quartz, pyrite, marcasite, sphalerite, galena, chalcopyrite, various sulphosalts, roscoelite, ankerite, calcite, fluorite and barite. The gold and precious metal tellurides are late in the paragenetic sequence.

Kelly and Goddard (1969) consider that the tellurium, gold and other hypogene vein constituents were transported into their deposition sites as soluble chloride complexes.

The veins exhibit shallow oxidation and weathering with the development of jarosite, limonite, tellurium oxides, supergene native tellurium, mercury, hessite, copper tellurides, native silver, silver halides and fine spongy gold in limonite ('rusty gold').

Disseminated and stockwork gold-silver deposits in igneous intrusive, volcanic and sedimentary rocks

These deposits cover a wide spectrum. Some occur in igneous plugs, stocks, dykes and sills; others occur in diffuse altered zones in volcanic flows principally of Tertiary and Mesozoic age; and still others are disseminated bodies in various types of sedimentary rocks.

The principal economic element in these deposits in gold with small amounts of silver. A few deposits yield the base metals, but they are generally not known as base metal deposits. The grade of the deposits is highly variable. Most are relatively low grade (<0.5 oz Au/ton) but are characterized by large tonnages. The Au/Ag ratio is variable being generally high in the older deposits and low in the younger deposits. Most deposits are characterized by the presence of quartz or by silicification, often on a wide scale. Some deposits, particularly those containing massive pyrite, pyrrhotite and arsenopyrite, have little quartz and are not marked by the effects of silicification. The elements commonly concentrated in these deposits, neglecting those in the common gangue minerals such as quartz, silicates and carbonates, are: Cu, Ag, Au, (Ba), (Sr), Zn, Cd, Hg, B, (Sn), Pb, As, Sb, Bi, V, S, Se, Te, Mo, W, (F), Fe, Co and Ni. Those in parentheses are infrequent or occur only in certain deposits.

These deposits can be classified into three categories. Those in igneous bodies, those in volcanic flows and those in specific types of sedimentary beds. Each type is best described by examples.

Disseminated and stockwork gold-silver deposits in igneous intrusive bodies

These deposits occur in igneous plugs, stocks, dykes and sills that have been intensely fractured or shattered and infiltrated by quartz, gold and other minerals. Most of the deposits are stockworks or diffuse irregular impregnations. The alteration processes vary with the type of rock. In granitic (acid) rocks sericitization, silicification, feldspathization (development of albite, adularia, etc.) and pyritization are predominant; in intermediate and basic rocks carbonatization, sericitization, serpentinization and pyritization prevail. Alunitization may occur in both acid and basic rocks in places.

Seven Canadian examples, one from Chile, two from U.S.S.R. and one from Zaire will illustrate this type of deposit – the Howey and Hasaga mines at Red Lake, Ontario; some of the orebodies in the Matachewan district, Ontario; the Box Mine at Goldfields, Saskatchewan; the Sunbeam Kirkland Mine in the Falcon Lake stock, southeastern Manitoba; the Baton Lake dyke near Indin Lake, Northwest Territories; the Lamaque Mine, Val d'Or, Abitibi County, Quebec; the Camflo Mine near Malartic Quebec; the El Chivato (Talca) Mine in Chile; the Berezovsk deposits in the Urals of U.S.S.R.; and the Twangitza deposit in Zaire.

The orebodies of the Howey and adjacent Hasaga Mine at Red Lake, both now exhausted, were developed in a quartz porphyry dyke intruding Keewatin volcanic breccia (Horwood, 1945, 1948*e*). The orebodies were sections of the porphyry dyke extensively fractured and infiltrated by gold-bearing quartz veins and stringers (Fig. 49). These zones of veins and stringers were marked by considerable alteration the

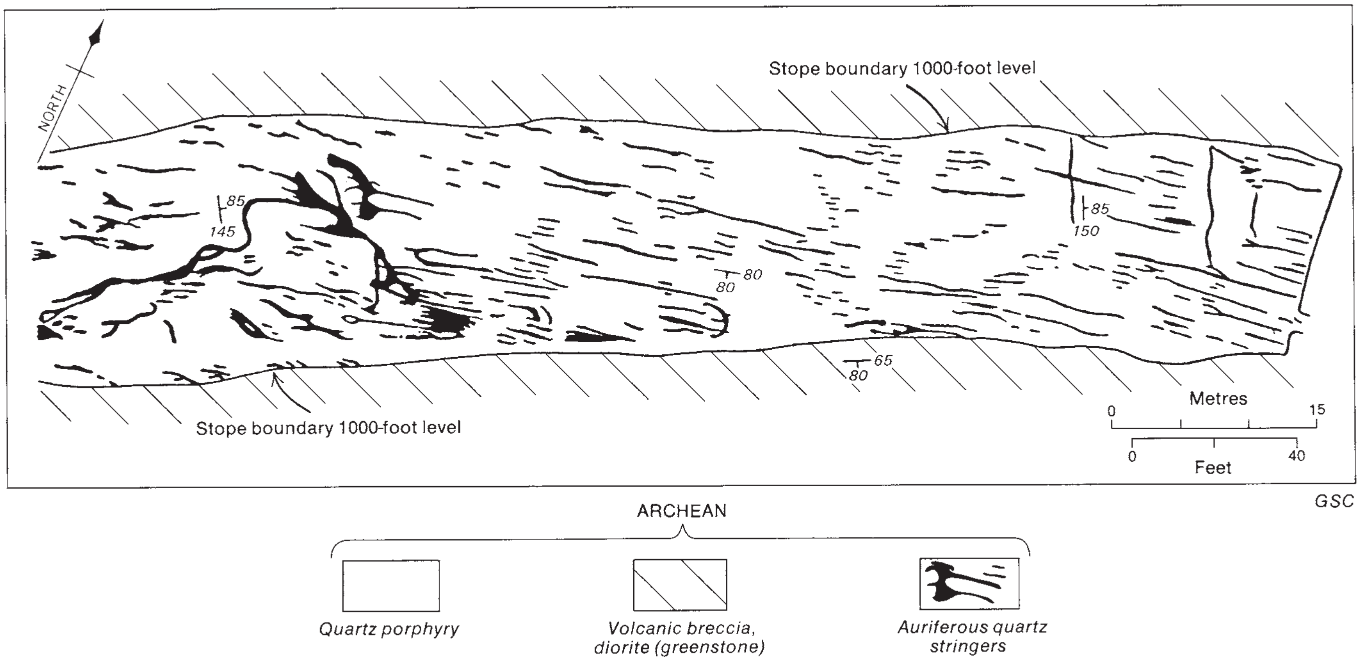

Figure 49. Sketch showing the distribution of auriferous quartz stringers in a portion of the quartz porphyry dyke, Howey Mine, Red Lake, Ontario (modified from Horwood 1945, 1948*e*).

principal processes being sericitization, albitization, carbonatization and pyritization. The principal minerals within the quartz veins and stringers included carbonates, pyrite, sphalerite and small amounts of galena, chalcopyrite, altaite and polybasite. The economic gold minerals were the native metal and small amounts of tellurides, mainly sylvanite. The grade of the orebodies averaged 0.10 oz Au/ton and 0.05 oz Ag/ton, giving an Au/Ag ratio of 2.

Some of the gold orebodies in the Matachewan district of Ontario are in syenite porphyry (Dyer, 1936). At the Young-Davidson and Matachewan Consolidated mines, now exhausted, porphyritic syenite bodies (mainly dykes) intrude Keewatin volcanics, including pillow lavas and agglomerate and Timiskaming conglomerate and greywacke (North and Allen, 1948; Derry *et al.*, 1948). In the Young-Davidson Mine (Fig. 50) the brick-red phase of the syenite contained 2 per cent of disseminated auriferous pyrite accompanied by minor amounts of chalcopyrite, galena, molybdenite, scheelite and specularite. Superimposed on this phase of the syenite are two sets of fractures, one containing quartz and carbonate veins usually less than 2 in. thick, and the other fine and hairlike containing visible gold. The average grade of the ore was 0.1 oz Au/ton and 0.02 oz Ag/ton, giving an Au/Ag ratio of 5. The ore in the prophyry of the Matachewan Consolidated Mine was similar to that in the Young-Davidson.

The orebody of the Box Mine at Goldfields, Saskatchewan, now abandoned, was somewhat similar to that described above for the Howey and Hasaga mines. The focus of mineralization was a granitic sill intruded into gneisses of the Tazin Group of possibly Archean age (Jewitt and Gray, 1940). The sill is marked by a stockwork of innumerable quartz veins and stringers developed in fractures and mineralized with small amounts of pyrite, galena, sphalerite and free gold. At least two and possibly three ages of quartz stringers occur. The wall-rock alteration in the heavily mineralized sections included sericitization and pyritization (*see* page 236). The grade of the ore averaged about 0.05 oz Au/ton, and the Au/Ag ratio of the orebody as a whole was about 5. In the general area there are a number of other similar deposits in granitic rocks (Alcock, 1936; Christie, 1953).

The Sunbeam Kirkland Mine, now abandoned, was developed in the quartz monzonite phase of the Falcon Lake stock (Fig. 51*a*) in the West Hawk Lake area of southeastern Manitoba (Brownell, 1941; Haugh, 1962; Gibbins, 1970). The deposit was a pipelike body (Fig. 51*b*) rudely circular in cross-section and plunging steeply to the northwest. The material in the pipe was highly fractured quartz monzonite that has been moderately to intensely sericitized, carbonated, silicified and impregnated with sulphides and gold. The sulphides, localized mainly along thin fractures, were pyrite, pyrrhotite, arsenopyrite, sphalerite, galena, tennantite and chalcopyrite. The gold was mainly free. Late fractures also carried some free gold. The average grade of the orebody was 0.23 oz/ton, and the Au/Ag ratio appears to be 1 according to analyses of ore samples carried out at the Geological Survey.

The Baton Lake dyke deposit some 30 mi north-northeast of the north end of Indin Lake, Northwest Territories is owned by Johnsby Mines Ltd. The deposit is a quartz stockwork in a quartz-albite (quartz diorite) dyke in andesites (greenstones) of the Yellowknife Supergroup. The dyke has been traced for some 20 000 ft and has an average width of about 110 ft. A host of glassy quartz veinlets and stringers occur in silicified parts of the dyke, follow definite fracture patterns, and range in width from a fraction of 1 in. to 2 ft or

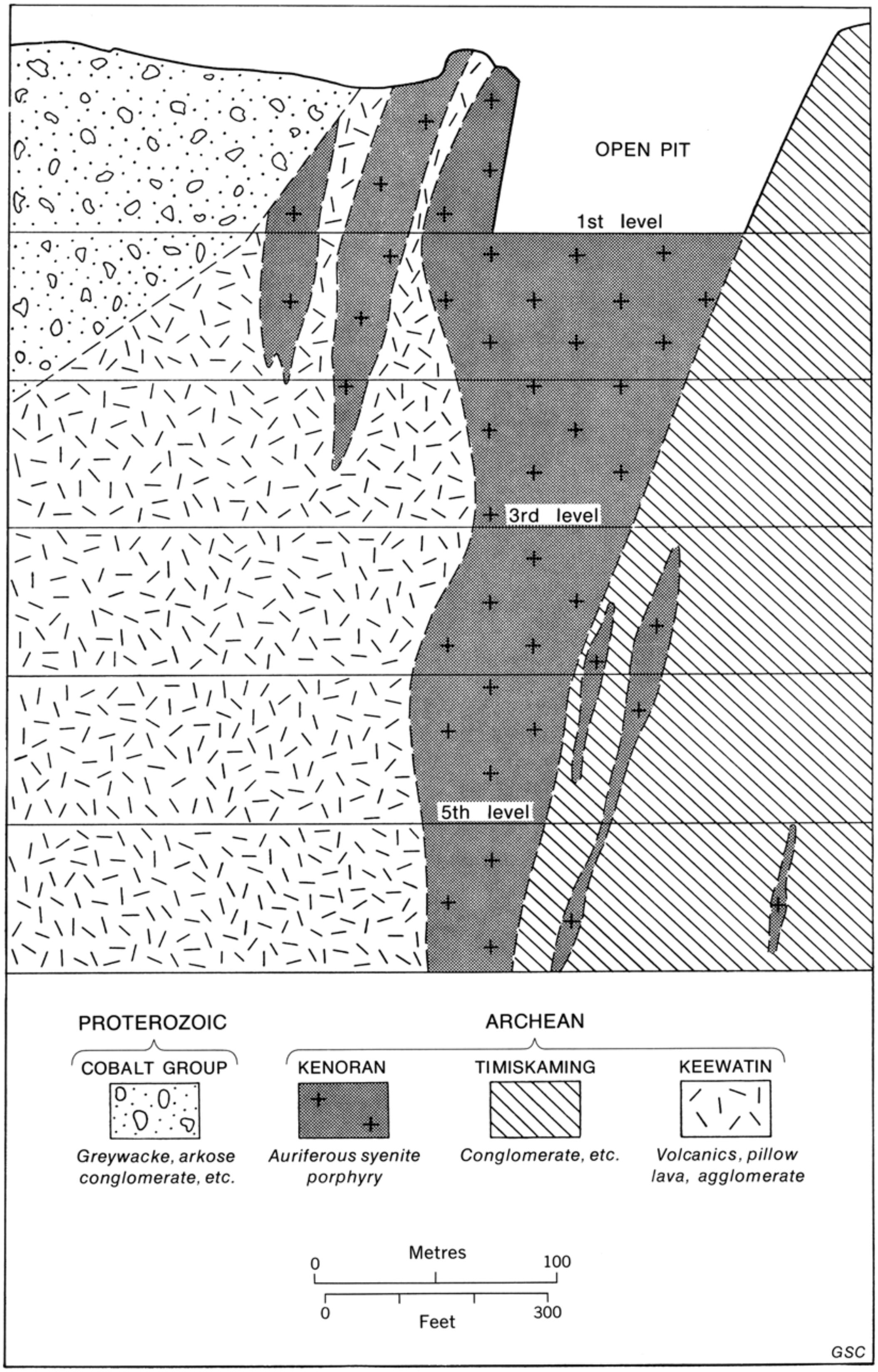

Figure 50. Typical north-south vertical section, Young-Davidson Mine, Matachewan, Ontario (after North and Allen, 1948).

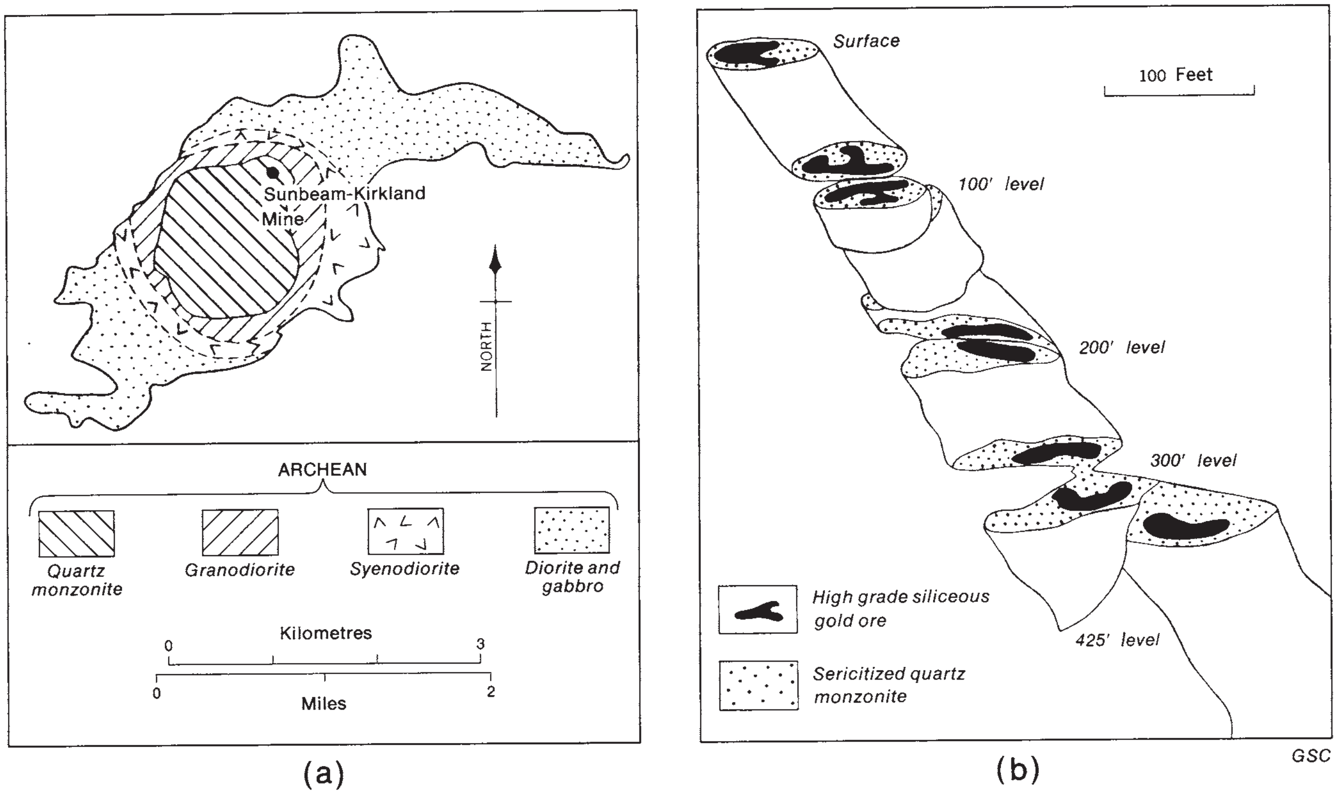

Figure 51. (a) General geology of the Falcon Lake stock, southeastern Manitoba. (b) Sunbeam-Kirkland auriferous pipe (after Brownell, 1941).

more. Most of the gold occurs free in the glassy quartz and is commonly associated with pyrite, pyrrhotite, arsenopyrite and sphalerite. In places there is some tourmaline in the quartz stringers. Pyrrhotite is abundant throughout the dyke and appears to be indigenous. It is reported that the deposit contains 15 million tons of ore averaging 0.068 oz Au/ton (Northern Miner, Aug. 3, 1972, p. 19). Assays quoted by Lord (1951) indicate an Au/Ag ratio of 1.1.

The Lamaque Mine at Val d'Or, Quebec is essentially in a granodiorite-diorite stock in Archean agglomerates and tuffs intruded by dykes and irregular masses of diorite porphyry (Wilson, 1948). The orebodies are veins or stockworks of quartz stringers in faults with little displacement (Fig. 52). The mineralization in the quartz consists of tourmaline, ankerite, scheelite, and small amounts of pyrite, chalcopyrite, native gold and several tellurides. Adjacent to most of the veins the wall rock is carbonatized, pyritized and tourmalinized for distances of a few inches to several feet. The average grade of the oreshoots is 0.32 oz Au/ton.

The geology and mineralization of the Lamaque orebodies are remarkably similar to those obtaining at the Morning Star Mine, Woods Point, Victoria, Australia (Clappison, 1953). There, the orebodies are in quartz veins in fissures in a diorite dyke that intrudes Upper Silurian slate and sandstone (Fig. 53). The quartz veins vary in width from a few inches up to 4 ft and are marked by flanking altered zones in which a fair amount of pyrite and quartz are developed. The mineralization in the quartz veins consists mainly of pyrite, with small amounts of galena, sphalerite, chalcopyrite and free gold, the last being commonly present in amounts of several ounces to the ton.

The Camflo Mine located between Malartic and Val d'Or, Quebec is in a highly fractured, moderately altered porphyritic syenite (monzonite) stock that intrudes Archean (Malartic and Kewagama groups) conglomerate, iron-formation, greywacke, phyllite and various volcanic rocks (tuff, andesite, diorite) (Meikle, 1970). The orebodies are zones marked by myriad white-grey quartz stringers and considerable amounts of disseminated pyrite. Calcite and fluorite are widespread in the ore zones, and minor amounts of scheelite are common. Small specks of visible gold occur in the quartz stringers, along minute fractures in the porphyry and coating the faces of pyrite crystals. Minor amounts of tellurides occur in places. Both the native gold and tellurides are late in the paragenetic sequence of minerals. One thousand tons per day are mined from the orebodies which average about 0.25 oz/ton Au. The Camflo orebodies resemble those of the Young-Davidson and Matachewan Consolidated mines described above.

Several other occurrences of large tonnage disseminated gold orebodies in shattered, sheared and fractured igneous bodies could be mentioned. One averaging in width from 60 to 100 ft, containing some 5 million tons carrying about 0.15 oz Au/ton occurs in shattered granodiorite at the Cochenour Willans Mine in the Red Lake area, Ontario (Northern Miner, Jan. 31, 1974, v. 59, no. 46, p. 1). Other possibilities of developing large low grade auriferous orebodies in granodiorite, syenite or other igneous type rocks would seem to be good in the Canadian Shield. Parts of the Kirkland Lake area

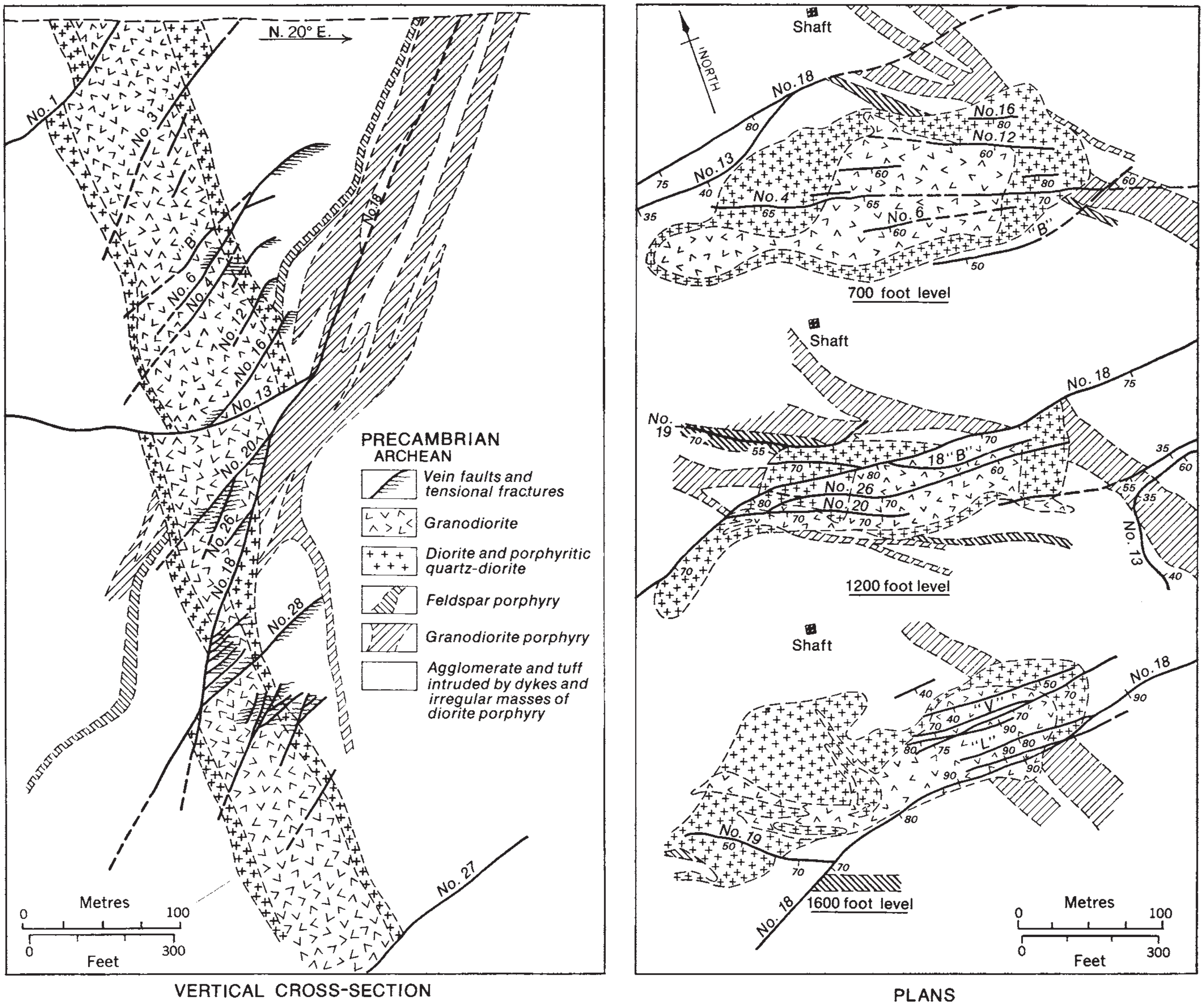

Figure 52. Plan and vertical cross-section transverse to veins, Lamaque Mine, Val d'Or, Quebec (after Wilson, 1948). (Compare with Figure 53.)

should be looked at in this respect since some of the syenites and porphyries are mineralized over considerable widths in places (*see* Burrows and Hopkins, 1925, p. 22).

Interesting and productive auriferous deposits of infrequent occurrence are certain gold-tourmaline-chalcopyrite circular and lenticular pipes developed mainly in small granitic stocks. The El Chivato (Talca) Mine in Chile about 150 mi south of Santiago is a striking example (Ruiz and Ericksen, 1962). The ore is altered and replaced granitic breccia cemented by quartz, carbonates and coarsely crystalline tourmaline. The brecciated granitic rock is of Late Jurassic to Late Cretaceous age. The sulphide minerals are pyrite, chalcopyrite, galena, sphalerite and tetrahedrite. Much of the gold is finely disseminated and commonly occurs as blebs in chalcopyrite. In Chile this type of deposit grades into or is associated with rich copper pipes characterized by abundant chalcopyrite and tourmaline with only small amounts of gold. According to Geier (1933) the orebodies are generally inverted cones. Most are highly oxidized and enriched in gold down to 200 ft or more.

Somewhat similar tourmaliniferous deposits occur in the eastern Transbaikal gold-molybdenum belt of the U.S.S.R. (Borodaevskaya and Rozhkov, 1974). The auriferous shoots of the Klyuchi gold deposit in this belt are developed in pipes, veins and irregular bodies localized in explosive (breccia) pipes at the intersection of fractures cutting mainly granites of unspecified Mesozoic age and Upper Cimmeric (Jurassic) minor intrusions. The host rocks are marked by an early phase of sericitization, chloritization, pyritization and silicification followed by an intense phase of auriferous quartz-tourmaline and quartz-sulphide veins and impregnations. The minerals include essentially pyrite, chalcopyrite, arsenopyrite and gold

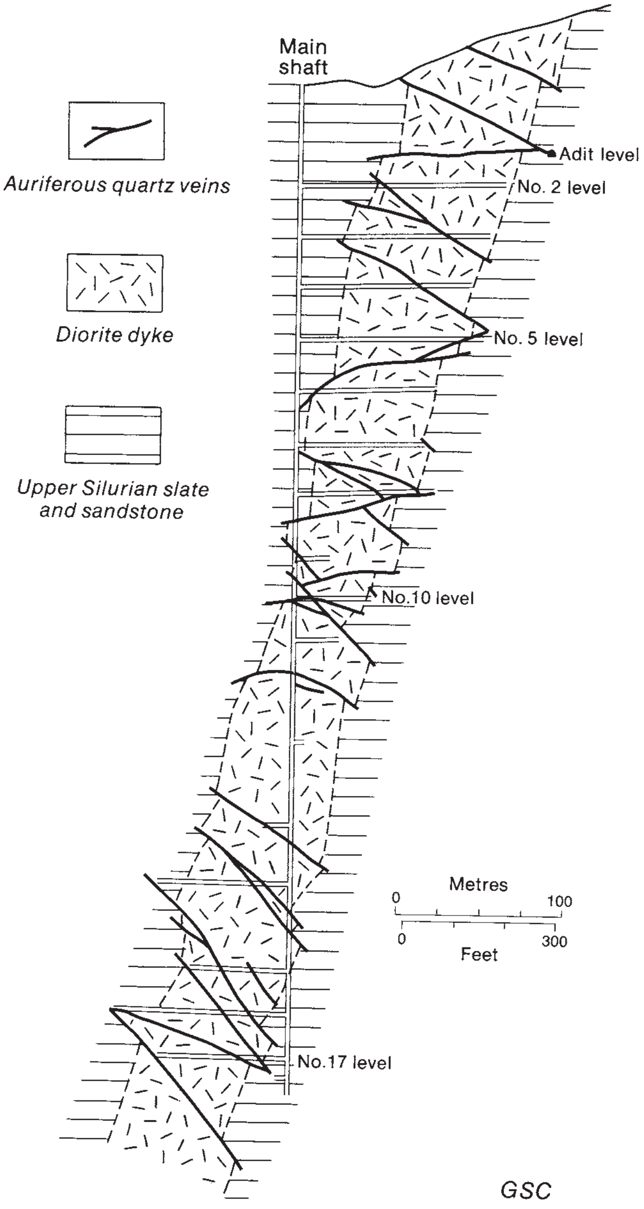

Figure 53. Typical north-south cross-section through the main shaft, Morning Star Mine, Woods Point, Victoria, Australia (after Clappison, 1953). (Compare with Figure 52.)

with minor amounts of freibergite, enargite, molybdenite, bismuthinite, native bismuth and a number of other sulphides and sulphosalts.

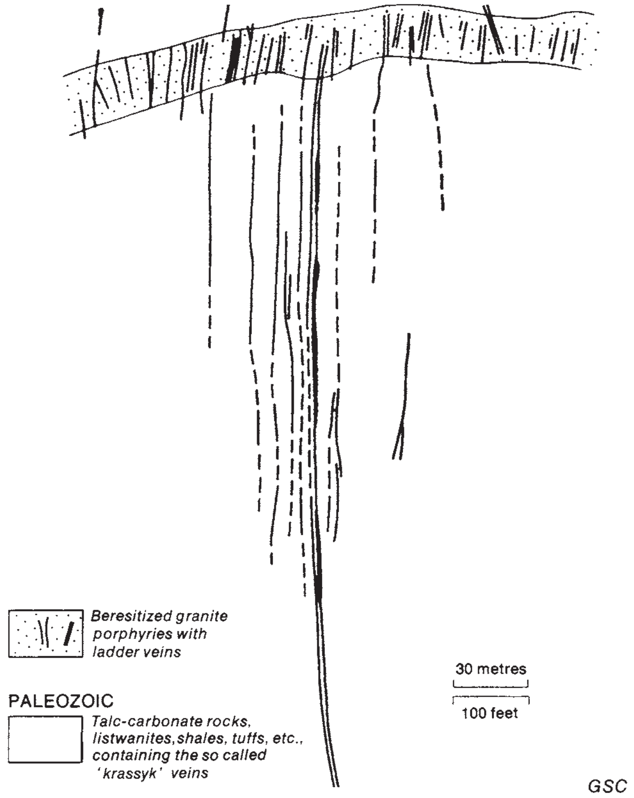

Figure 54. Generalized geological plan of the Molokova deposit, Berezovsk, Urals, U.S.S.R. showing auriferous ladder veins in beresitized granite porphyry dykes and the so-called gold-bearing 'krassyk' quartz veins in sedimentary, volcanogenic and basic-ultrabasic intrusives (after Borodaevskaya and Borodaevskii *in* Borodaevskaya and Rozhkov, 1974).

The Beresovsk deposits in the Urals, U.S.S.R., discovered in 1745 and now largely exhausted, are typical examples of gold deposits in igneous dykes and stocks. The Beresovsk district some 10 mi northeast of Sverdlovsk is underlain by Paleozoic mica schists and serpentinites intruded by Hercynian granitic bodies (Mushketov, 1930; Borodaevskii and Kytyukin, 1939; Boradaevskaya and Rozhkov, 1974). Intruding the schists in a fairly well-defined zone are a large number of imbricating quartz porphyry and microgranite dykes 10 to 150 ft wide, with a northerly strike and mostly vertical to steep dips, some of which are intersected by a network or ladder-vein system of quartz veins and stringers, a few inches to 3 ft or more wide (Fig. 54). Adjacent to the quartz veins and commonly throughout the quartz porphyry a type of alteration called beresitization occurs. This alteration is a combination of sericitization and pyritization with feldspathization in places. The veins consist of quartz, sericite, tourmaline, auriferous pyrite, galena, chalcopyrite, aikinite, covellite, magnetite, sphalerite, tetrahedrite and gold. The grade of the deposits ranges from 0.25 to 0.50 oz Au/ton. The Au/Ag ratio is about 8. At Pyschminsk some 5 mi northeast of Beresovsk similar quartz veins occur in a complex of sedimentary schist, serpentine and quartz porphyry. Most of the ladder-vein quartz zones lie within the quartz porphyry, but others are in the serpentinite, which is altered to listwänite, actually a carbonated (magnesite, dolomite), sericitized, pyritized, talcose serpentinite with quartz. Associated with the ladder veins in the Berezovsk goldfield are zones of so-called 'krassyk' veins in the sedimentary, volcanogenic and basic-ultrabasic country rocks. These are similar in strike and dip to the ladder veins in the dykes; their mineralization comprises drusy quartz with subordinate amounts of ankerite, calcite, dolomite, pyrite, tetrahedrite, scheelite, aikinite, galena and chalcopyrite.

The Twangitza gold deposit in Kivu Province, Zaire is in highly carbonated albitites (Safiannikoff, 1972). The mineralization is localized in an anticlinal zone in which black schists and quartzites of the Burundian system (Precambrian) were intruded by albitites. The albitites are composed essentially of albite and 25 to 30 per cent ankerite. There is practically no quartz. Most of the gold is associated with pyrite and arsenopyrite that is disseminated through the albitites. Some monazite is also disseminated through the albitite and adjacent rocks. Ankerite-pyrite-arsenopyrite-quartz veinlets form a few stockworks in fractured zones outside the albitites. The gold is very fine grained, and very little responds to amalgamation. The grade of the orebodies averages about 3 to 5 ppm (0.08–0.14 oz Au/ton). Safiannikoff likens the deposit to those at Beresovsk in U.S.S.R. and some of those at Kilo-Moto.

In closing this section it should be pointed out that gold deposits in igneous bodies are common. There is a marked relationship in many gold belts between albitites, albite porphyries, quartz-feldspar porphyries and gold. It is not always clear just what this relationship is. In most places the localization of the gold deposits in or near the porphyries has been ascribed to the structural competence of these rocks relative to the host rock. In other words they fractured more readily and formed structural sites for the orebodies. The origin of the various porphyries in gold belts is itself a major problem. Some seem to be of magmatic origin and are perhaps a differentiate either of a granitic magma or of granitization processes. Others appear to have formed by replacement from solutions or by diffusion. These various hypotheses have been discussed by Henderson and Brown (1966) and by Boyle (1961*a*, 1976*a*). In many places the pyrite, ankerite and gold appear to have been largely indigenous; in others they appear to have been partly redistributed during shearing and fracturing. Moorhouse (1942) mentions a number of these gold-bearing albitite dykes and porphyries in the gold belts of Canada; he thinks that the gold mineralization of some of the bodies is a differentiate more or less *in situ* of the bodies themselves. In the western San Juan Mountains, Colorado, Lipman *et al.* (1976) emphasize the relationship in space and time of the gold and base metal mineralization to volumetrically minor intrusions of quartz-bearing silicic porphyry, which post-dates the magmatic events that gave rise to the various volcanic caldera.

Disseminated gold-silver occurrences in volcanic flows and associated volcaniclastic rocks

Commercial deposits of this type have not been worked. Most occurrences are very low grade commonly less than 0.01 oz Au/ton (0.3 ppm). Silver contents are higher in places, averaging in some cases 3.5 oz Ag/ton (120 ppm).

The disseminated occurrences in this category are in reality large irregular and diffuse zones of alteration manifest mainly in rhyolites, andesites, basalts and their associated tuffaceous rocks. These zones of alteration constitute silicification, sericitization, epidotization, argillization or alunitization, commonly associated with pyritization and carbonatization. In the basic and intermediate rocks the effects are commonly collectively called propylitization. Large volumes of the volcanic country rocks are affected, giving them a bleached and altered aspect. Locally diffuse silicified zones, quartz veins, alunite veins and pyrite veins and segregations ramify through the altered rocks.

Such extensively altered zones of rock, in places carrying small amounts of gold and silver, are widespread in Mesozoic-Tertiary volcanic terranes throughout the world. They are particularly common in the western United States, in Japan, Indonesia, New Zealand (Coromandel Peninsula) and elsewhere. Some are closely associated with gold deposits as at Goldfield, Nevada (Fig. 32), Virginia City (Comstock Lode) (Fig. 33) and Titiribí, Colombia (Hoffmann, 1931). Most are of Tertiary age, but some such as those on Vancouver Island described by Clapp (1915) are of Mesozoic age. Others in British Columbia such as the Mount Edziza (Souther, 1967) and other volcanic complexes are of Tertiary age. One occurrence near Barstow, California is said to contain some 50 million tons containing an average of 3.5 oz Ag/ton (E.A. Schiller, pers. commun., 1968). The gold content is not known. The silicified and altered zones at Goldfield, Nevada range in gold content from about 0.02 to 3 ppm, the corresponding silver values are 0.3 to 10 ppm (Ashley and Keith, 1976). Deposits of this type mentioned in the Russian literature (Petrovskaya, 1974) appear to range widely in their gold and silver contents (Au – 0.02–3 ppm; Ag – 0.5–8.6 ppm).

Little can be said about the details of these occurrences since they have not been extensively studied. Most contain considerable amounts of fine-grained quartz, chlorite, epidote, sericite, adularia in places, clay minerals, carbonates and pyrite. Some are marked by developments of alunite as at Goldfield, Nevada (Jensen *et al.*, 1971; Ashley, 1974; Ashley and Keith, 1976). Those rich in pyrite appear in many cases to contain the most gold and silver. These altered and mineralized zones require detailed sampling and analysis before any conclusions can be drawn as to their commercial value.

Disseminated gold-silver deposits in volcaniclastic and sedimentary beds

These deposits are usually conformable with the sedimentary and volcaniclastic beds although in some cases their limits may infringe irregularly on overlying or underlying rocks. Some are large and of relatively high grade; others are commonly too low grade or not of sufficient tonnage to merit attention.

Two general categories of these deposits can be recognized – those developed in tuffaceous rocks and iron-formations within volcanic terranes and those resulting from extensive infiltration or replacement of chemically favourable beds such as limestones. The first is especially common in Precambrian terranes, although there is no reason why they should not occur in rocks of younger age; however, examples of the latter are rare to date. The second can apparently occur in rocks of any age. These deposits are best illustrated by specific examples.

Disseminated deposits in tuffaceous rocks and iron-formations

Gold deposits in tuffs and other volcaniclastic rocks are common in the greenstone belts of the Canadian Shield and in other greenstone belts of Precambrian age throughout the world. The Madsen Mine at Red Lake, Ontario will serve as an example of an extensive gold deposit in tuff (Horwood, 1945; McIntosh, 1948; Harriman, 1965).

The country rocks in the vicinity of the Madsen deposit are predominantly Keewatin volcanics consisting of meta-andesite pillow lavas with interbedded tuffs, agglomerate and breccia of acid to intermediate composition. Included in the volcanic pile are quartz and feldspar porphyries, which probably represent flows although the quartz porphyry that forms the upper contact of the ore-bearing tuff may be a dyke or sill.

The orebodies at the Madsen Mine all lie mainly within tuff beds and were localized by the action of rolls in the quartz porphyry on the hanging wall and in the talc schist and andesite on the footwall. The ore zones (Fig. 55) consist of silicified and heavily mineralized lenses in sheared tuff. The silicification in some places may be original (that is the rock was initially a cherty tuff), although there are narrow stringers of quartz and greenish quartz-carbonate containing visible gold that cut through the lenses in places. The lenticular ore zones, defined by assay, consist mainly of silicified tuff, abundant pyrite and small to minor amounts of magnetite, pyrrhotite, arsenopyrite, sphalerite and chalcopyrite. The average grade of the orebodies is 0.23 oz Au/ton and the Au/Ag ratio is about 5.5.

Gold-silver deposits in the various facies of iron-formations are particularly numerous in Precambrian rocks, especially those in greenstone belts of Archean age. Numerous examples can be cited including one of the orebodies in the Hard Rock Gold Mine near Geraldton, Ontario; orebodies in the Central Patricia Mine, Crow River district, Ontario; possibly the orebodies of the Homestake Mine, Lead, South Dakota; probably the orebodies of the Morro Velho, Raposos and Passagem de Mariana deposits in the 'Quadrilátero Ferrífero'), Belo Horizonte area, Minas Gerais, Brazil; and possibly some of the conformable gold-bearing sulphide orebodies in the Kolar goldfield, India. Certain gold deposits in the Precambrian of Africa also belong in this category, e.g., some of those in Rhodesia and the Moto deposit in Zaire.

The orebodies of the Central Patricia Mine in the greenstone belt in the Crow River area north of Lake St. Joseph in northwestern Ontario were in iron-formation (Thomson, 1939*a*; Barrett and Johnston, 1948). The iron-formation is banded and composed of layers of magnetite, chert (quartz) and siderite. The orebodies consisted of quartz and sulphide stringers and narrow veins that crossed the banded iron-formation at a large angle but were confined almost entirely to the iron-formation (Fig. 20). The gold-bearing stringers were mineralized heavily with pyrrhotite and arsenopyrite, and minor amounts of pyrite, chalcopyrite, siderite and chlorite. Nearly all of the gold was present as native metal in a finely divided form (<200 mesh) in minute fractures and on the crystal faces of the sulphide minerals. The individual stringers assayed up to 11 oz Au/ton, but the stockwork orebodies averaged about 0.33 oz Au/ton.

Numerous other gold deposits occur in iron-formation and related rocks in the Canadian Shield, particularly in Ontario. Here may be mentioned deposits and occurrences in the Pickle Lake, Casummit Lake, Michipicoten and Goudreau, Beardmore, Kirkland Lake and Emerald Lake (Timagami Forest) areas.

An interesting example of auriferous tuffs in a sedimentary terrane is provided by the occurrences at the Andrew Yellowknife claims some 70 mi northwest of Yellowknife, Northwest Territories (Lord, 1951). The country rocks are metasedimentary strata of the Archean Yellowknife Group comprising impure quartzites, quartz-mica schists, andalusite schists, sericite schists and biotite hornfels. Interbedded with these are beds up to 1600 ft in strike length of dark grey to black amphibolite, biotite-garnet schists and biotite-chlorite-garnet schists containing abundant pyrite in streaks, blebs and irregular masses. Vein quartz occurs irregularly along the beds but appears to bear no particular relationship to the pyrite. These pyritic schists appear to have originally been sulphidic tuffs and sediments (possibly silicate and sulphide facies of iron-formation?), now metamorphosed to pyritic amphibolites and pyritic schists during granitization processes, the manifestation of which is evidenced by a granitic batholith and pegmatites nearby. Some of the pyritic amphibolites contain significant gold assays, as high as 0.22 oz/ton across 7 ft. Native gold occurs sparingly in parts of the beds, but most of the gold is intimately associated with the pyrite in an invisible form. Beds, probably sulphidic tuffs and sediments (iron-formation?), similar to those at the Andrew Yellowknife property are common in other parts of the Yellowknife Supergroup. All are indicated by their rusty brown (limonitic) outcrops; most contain some gold and silver but rarely in economic amounts.

The famous Homestake Mine at Lead, South Dakota obtains its ore from a complex of inclined mineralized pipes, pods, veins, saddles and lenses developed along the crests of plunging folds within the Homestake Formation (McLaughlin, 1931; Gustafson, 1933; Noble, 1950; Slaughter, 1968; Norton, 1974). This formation is of Precambrian age and is said to have been originally an Fe-Mg carbonate bed some 60 ft thick in the early description by McLaughlin. Slaughter also characterizes the formation as originally an Fe-Mg carbonate sediment, now a sideroplesite-quartz schist with some banding due to differing amounts of graphite in the outer metamorphic zone. In the high grade metamorphic zones the sideroplesite schist has been converted to cummingtonite schist. The formation has been isoclinally folded and then cross-folded resulting in numerous contorted zones. Dilation in zones of cross-folding, mainly on the crests of folds, has been postulated as the cause of ore localization (Fig. 56).

According to Slaughter (1968) chloritization of the cummingtonite or sideroplesite schists is the most widespread effect of the mineralization, which he divided into four stages. The principal minerals of the first stage are quartz, chlorite and arsenopyrite; in the second stage, quartz, ankerite and pyrrhotite. In the third stage only pyrrhotite was deposited. The fourth stage followed the intrusions of Tertiary dykes, which occur throughout the area. It consisted mostly of pyrite and calcite. Gold accompanies all stages and is always the last mineral to be deposited. It is most closely associated with arsenopyrite of the first stage but can be interpreted as having been deposited during the fourth stage and superimposed on the products of the earlier stages. Noble (1950) mentions the presence of galena, sphalerite, chalcopyrite, marcasite, tetrahedrite, magnetite and specularite in the ores. The last two are fairly widespread.

The average grade of the Homestake orebodies is about 0.4 oz Au/ton, and their Au/Ag ratio is about 4. The average fineness of the native gold, as given by Slaughter, is 820.

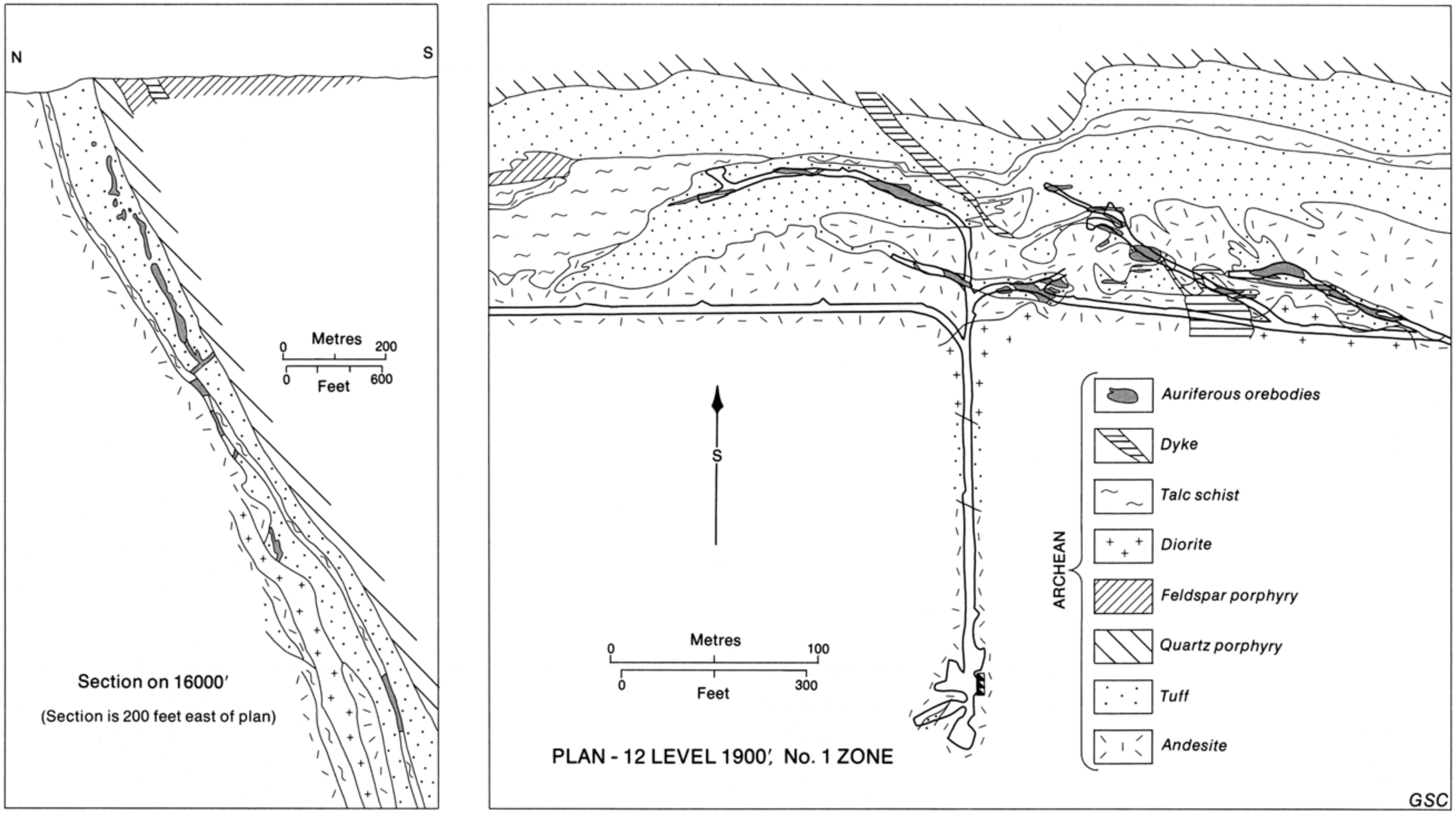

Fig. 55. Characteristic plan and section, Madsen Mine, Red Lake, Ontario (after Harriman, 1965).

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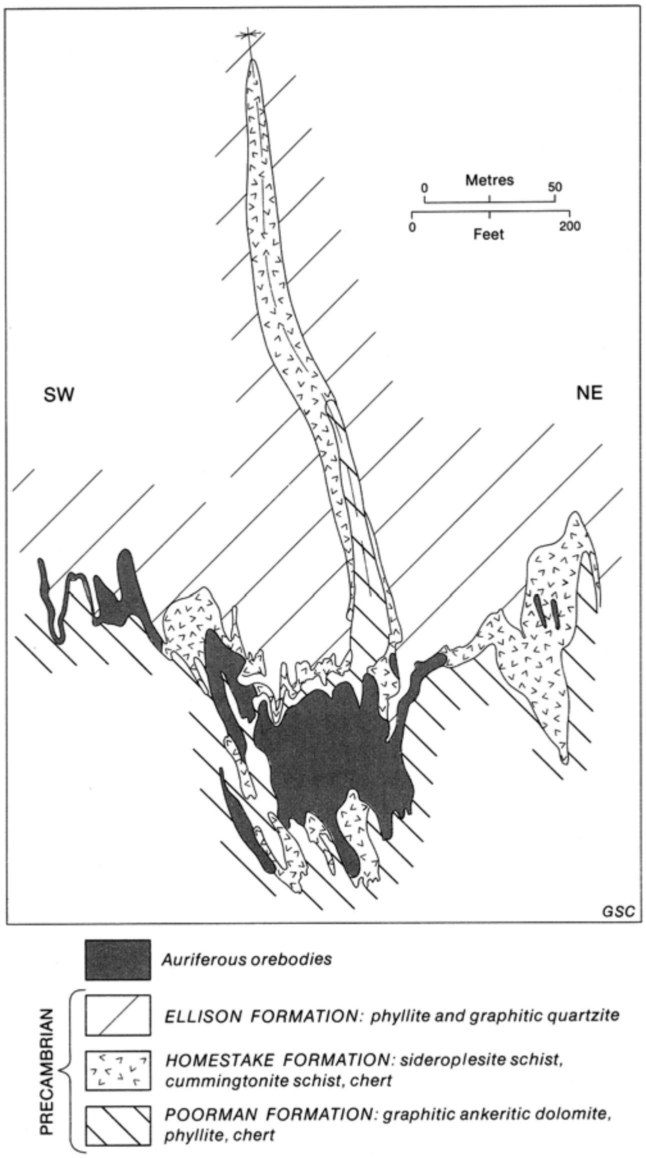

Figure 56. Vertical cross-section of the Main Orebody, Homestake Mine, South Dakota (after Noble, 1950). The isoclinal axis of the Pierce anticline is strongly deformed by a cross-fold, and the orebodies are localized in the zone of cross-folding.

Some investigators consider the deposit to be of Precambrian age; others have considered that the gold mineralization is Tertiary, since deposits of this age occur in the near vicinity. The orebodies in the Homestake Mine are, however, cut by Tertiary intrusives and faults, and the sulphur isotopic ratios of the sulphides in the Homestake are fundamentally different from those of the Tertiary deposits (Rye and Rye, 1974). It thus appears from these data that the gold was deposited during Precambrian time. The fineness of the gold is, however, low for Precambrian deposits, a feature that requires explanation.

Recently, on the basis of lead isotopes in galena from quartz veins, Rye *et al.* (1974*a*) concluded that the ore in the Homestake Mine was emplaced by metamorphic secretion from a 2.5 billion-year-old source (i.e., the Homestake Formation) during regional metamorphism and intrusion that occurred 1.6 billion years ago. The lead isotopes in Tertiary galenas from Paleozoic and Precambrian host rocks were found to have had different growth histories. The Tertiary galenas in Paleozoic rocks did not derive their lead entirely from Tertiary intrusive rocks in the area, but rather the lead may have been obtained mainly or in part from the Paleozoic rocks. Tertiary galenas in Precambrian rocks, on the other hand, seem to have obtained their lead largely from the transected metasedimentary host rocks or from the underlying basement, with little or no contribution from other sources.

The Homestake deposit is difficult to classify. Some have considered it to be simply a hydrothermal replacement deposit of favourable sedimentary carbonate rocks; other views now current consider that the Homestake deposit is confined to beds of carbonate iron-formation and that the gold and associated sulphides, original constituents of the iron-rich sediments, were later concentrated in dilatant zones during metamorphism (Sawkins and Rye, 1971, 1974). Sulphur, oxygen, carbon and lead isotopic data support this hypothesis (Rye and Rye, 1974; Rye *et al.* 1974*a*).

Deposits somewhat similar to those at the Homestake Mine occur in the vicinity of Contwoyto Lake, Northwest Territories, Canada (McConnell, 1964*b*; Tremblay, 1966; Bostock, 1967, 1968). There, layers and lenses of pyrrhotite and pyrite-bearing amphibolites (cummingtonite gneisses) are interbedded with Archean (Yellowknife Supergroup) greywacke and argillite and their metamorphic equivalents, nodular (cordierite and andalusite) biotite schist and gneiss. These layers and lenses of amphibolites and sulphide-bearing amphibolites are generally less than 60 ft thick and are thought by Bostock (1967, 1968) to be the metamorphic equivalents of an oxide-silicate-sulphide facies of iron-formation. An alternate explanation is that they are metamorphic replacements of carbonate layers or bands in an argillite-greywacke assemblage. To the writer the iron-formation hypothesis seems more probable.

The richest gold-bearing parts of these sulphide bands and lenses are in highly contorted areas, especially on the crests of folds where some secondary quartz stringers and small lenses are developed. The principal minerals in these sites are garnet, cummingtonite, quartz, pyrite, pyrrhotite, arsenopyrite, loellingite, chalcopyrite and native gold. Samples of this type of material are said to run from 0.07 to 0.65 oz Au/ton and 0.04 to 0.24 oz Ag/ton. The highest gold values appear to be concentrated in the arsenopyrite and loellingite-rich zones.

The gold deposits within the Quadrilátero Ferrífero, Minas Gerais, Brazil have been the subject of study for many years, and their origin has been variously interpreted. The principal mines are the Morro Velho, Raposos and Passagem de Mariana. The mineralogy of the orebodies in these mines is essentially similar. The economic mineral is native gold accompanied by pyrite, pyrrhotite, arsenopyrite, chalcopyrite and small to minor amounts of tetrahedrite, bornite, sphalerite, galena, stibnite, wolframite and scheelite. The gangue is quartz and ankerite, whose origin has been variously interpreted as original, redistributed during metamorphism, or introduced by hydrothermal solutions. In the Morro Velho and Raposos mines the sulphide content of the ore ranges from low amounts up to 50 per cent or more. Tourmaline is especially abundant in the Passagem deposit. The grade of the ores ranges from 0.25 to 0.5 oz Au/ton and the Au/Ag ratio is about 5 for most mines.

Recent descriptions of the country rocks in the "Quadrilátero Ferrífero" are given by Gair (1962), Dorr and Barbosa (1963), Barbosa (1968), Dorr (1969) and Fleischer and Routhier (1973). The rocks of interest are the Rio das Velhas Series and Minas Series, which include a great pile of Precambrian sediments comprising quartzite, phyllite, chert, black graphitic schist, chlorite schist, ferruginous quartzite, quartz dolomite-ankerite rock (Lapa Seca) and what seem to be from the descriptions and samples several facies of iron-formation including oxide, carbonate, silicate and sulphide facies. The terminology is somewhat confusing to say the least and is not helped by differences of opinion as to what constitutes itabirite (oxide facies of iron-formation) and other weathered products of iron-formations (Park, 1970; Dorr 1971). It appears from the literature that there are also serious problems in unravelling the stratigraphy and differences of opinion on the succession of rocks, facies changes, etc. These controversies, notwithstanding, there is considerable evidence to indicate that the three major gold deposits of the district, and numerous other smaller deposits, are either in or closely associated with one or other facies of iron-formation.

The best descriptions of the Morro Velho Mine is by Matheson (1956) and Gair (1962). The orebodies occur within a highly contorted siliceous banded dolomite-ankerite rock (Lapa Seca) that is probably the equivalent of the carbonate facies of iron-formation (Fig. 57). The rocks enclosing the Lapa Seca are quartz-carbonate-sericite-chlorite and graphitic schists. The main orebody is a flattened pipe that stands edgewise and plunges eastward to a depth exceeding 8000 ft. The other orebodies are ramifying, irregular, contorted and sinuous. The ore is particularly rich in sulphides, especially pyrrhotite and arsenopyrite. Some parts of the orebodies are nearly massive sulphides. The grade averages about 0.4 oz Au/ton.

The Raposos Mine about 3 mi northeast of the Morro Velho Mine has been described by Gair (1962) and Tolbert (1964). The orebodies are long, narrow sinuous bodies composed mainly of quartz, ankerite, pyrite, pyrrhotite and arsenopyrite in iron-formation, mainly the siderite facies. The gold occurs mainly in the native form, and the grade ranges from 9 to 16 g Au/ton (0.27 to 0.47 oz/ton).

The Passagem de Mariana gold deposit, in the southeastern part of the "Quadrilátero Ferrífero", has been described by Barbosa *et al.* (1948) and more recently by Fleischer and Routhier (1973). The orebodies, composed essentially of quartz, carbonates, tourmaline, arsenopyrite and gold, occur in a sedimentary horizon averaging some 5 m in thickness and extending over a distance of 15 km. The ore-bearing horizon (Batatal Formation according to Fleischer and Routhier) consists of graphitic phyllites, ferruginous dolomite and metacherts. The hanging wall is iron-formation (itabirite) and the footwall sericitic quartzite. The orebearing horizon has been considerably deformed, and in detail some of the orebodies are composed of boudins of tourmalinite containing arsenopyrite and gold, whereas others consist of tourmalinite with gold and sulphides in quartz and coarse dolomite.

The origin of the gold deposits of the "Quadrilátero Ferrífero" have been variously interpreted. Lindgren (1933),

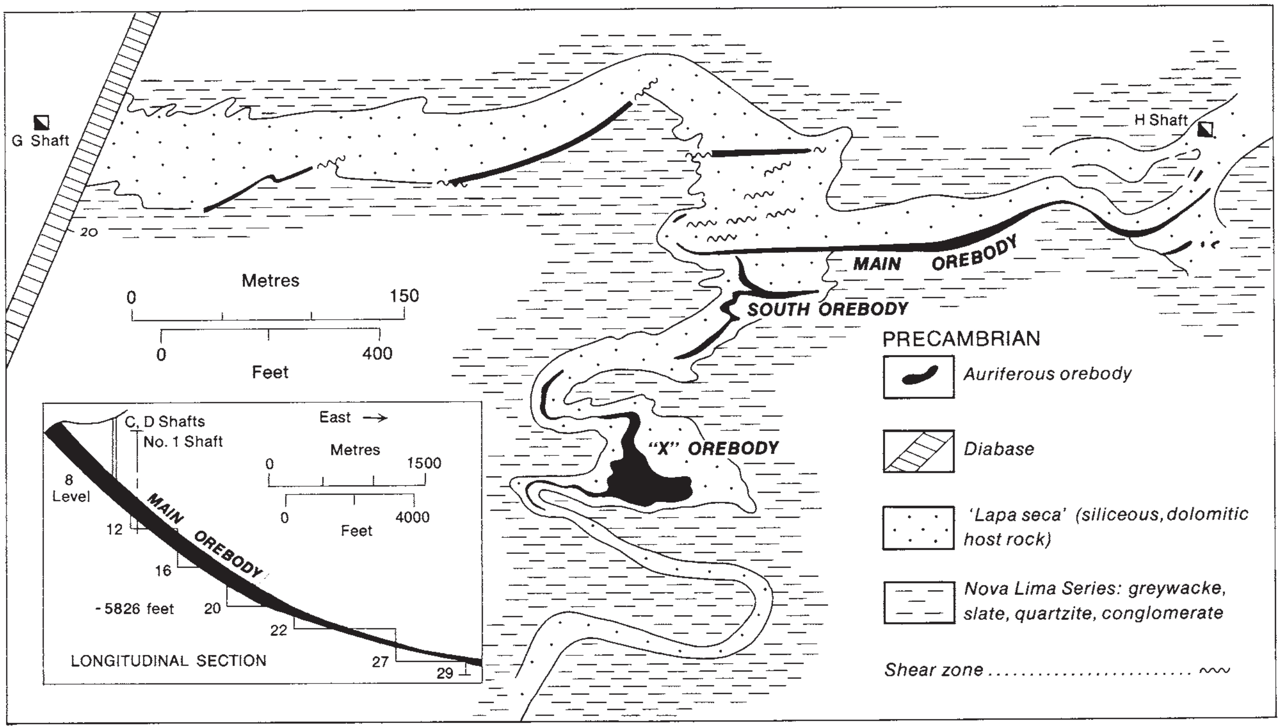

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Figure 57. Geological plan 20 level (5826 ft below collar) and generalized longitudinal section, Morro Velho Mine, Minas Geraes, Brazil (after Matheson, 1956).

Matheson (1956), Gair (1962), Dorr (1969), and Park and MacDiarmid (1970) considered that the Morro Velho deposit was typically hydrothermal, the gold and other constituents presumably being derived from some underlying granitic body, although most of the authors are rather vague on the exact magmatic source of the elements in the deposit. Fleischer and Routhier (1973), on the other hand, think that the Morro Velho deposit is consanguineous-syngenetic, the gold and other elemental constituents being syngenetic with the chemical sediments and later remobilized and concentrated in favourable sites during structural deformation and metamorphism. This view has been disputed by Barbosa *et al.* (1974).

Tolbert (1964) considered the Raposos Mine to be a hydrothermal deposit but found no evidence for the ultimate origin of the gold. He considered the enclosing Precambrian rocks and a granitic body as possible sources of the precious metal. He thought that the iron, sulphur, arsenic and small amounts of chromiun in chromium sericite associated with the orebodies may have been derived from a local source.

A wide variety of origins has been suggested for the Passagem de Mariana deposit. Hussak (1898) considered the deposit to be a mineralized pegmatite, and Derby (1911) and others following him considered the ores to be of hydrothermal origin. Fleischer and Routhier (1973) think the deposit is a remobilized-syngenetic one, the gold and other constituents of the ores being an integral part of the chemical sediments in which the deposit is localized. This view has been disputed by Barbosa *et al.* (1974) who apparently think that the deposit is a hydrothermal bedding vein.

Numerous other examples of gold deposits in or near iron-formation occur in the Precambrian shields of the world. In Africa, Woodtli (1961) describes gold impregnation deposits in the Moto area of Zaire. The orebodies are in a Precambrian schistose rock containing ankerite, quartz and albite near itabirite (iron-formation) and graphitic schist. The mineralogy of the orebodies comprises quartz, albite, ankerite, siderite, magnetite, hematite, pyrite, pyrrhotite and native gold, the last rarely visible. The gold-bearing shoots are irregular and are outlined by assay. In Rhodesia, Lightfoot (1930), Pelletier (1964) and Anhaeusser (1976) mention that a number of the gold-quartz-sulphide deposits are in Precambrian banded ironstones. Pyrrhotite figures prominently in these deposits as it does in most auriferous orebodies in iron-formation throughout the world. The Wanderer Mine was a prolific producer until its exhaustion in 1952. More recently Fripp (1976) has described the stratabound gold deposits in Archean banded iron-formations in Rhodesia. He thinks that the gold-bearing sulphide-rich layers in the deposits predate the metamorphism and deformation of the iron-formation and the enclosing aquagene lavas and tuffs, and proposes that the sulphides, carbonates, chert and gold represent primary (syngenetic) sedimentary accumulations on the sea floor. These constituents were precipitated from geothermal brines during fumarolic-stage volcanic activity in Sebakwian (early Precambrian) times. These brines contained the gold as dissolved complex species with hydrogen and sulphur, and possibly with arsenic. The depth of the sea water, temperature and pH largely controlled the nature and gold content of the iron-formation.

In Tanzania some of the gold deposits in the Iramba-Sekenke goldfield are extensive impregnations of pyrite, pyrrhotite and gold in Precambrian banded quartzite and iron-formation; similar auriferous impregnation deposits are worked in the Southwest Mwanza goldfield, in the Musoma goldfield, in the Kahama-Nzega-Shinyanga area and elsewhere (Harris, 1961). Many of the deposits in the Lupa goldfield, likewise, appear to occur in sedimentary banded iron-formations (Grantham, 1928), although there has been a general dispute about the origin of some of these ironstones (Kondakov and Perunov, 1973).

In Australia gold-quartz veins and disseminations of gold are known in banded iron-formation in the Lennonville, Boogardie (Finucane, 1953) and north of Lake Austin goldfields, Western Australia and in the Tennant Creek district of Northern Territory (Sullivan and Ivanac, 1953; Crohn, 1965; Baxter, *in* Knight 1975; Woodall, 1975; Ryan, 1976). The ironstones and jaspers in the Tennant Creek area are apparently not iron-formations in the ordinary sense. Some appear to be replacement bodies in faults and shear zones. The gold-bismuth-copper Juno lode for instance is a discordant magnetite- and hematite-rich ellipsoidal to pipelike body cutting Lower Proterozoic felsic sediments and pyroclastics. Massive magnetite and abundant chlorite constitute the core of the lode, and gold is concentrated therein. Both the ore minerals and gangue minerals are vertically zoned within the lode (Large, 1974, 1975). Most are closely associated with hematitic shale and may have originated by mobilization and concentration of iron from these sediments. Crohn (1965), however, considered this improbable basing his conclusion on trace element analyses of the hematite from the two types of occurrences. Actually, the origin of the Tennant Creek lodes has been a controversial topic for years. Recently Dunn (1976) considered that the auriferous deposits of the Tennant Creek field are examples of the "massive oxide" facies of volcanogenic mineral deposits. In reply Large (1976) agreed that the ores could be considered as massive oxide equivalents of volcanogenic massive sulphide ores, but maintained that the Juno orebody is a subsurface replacement deposit and has significant differences from typical proximal massive sulphides deposited at the seawater-rock interface. In the Yilgarn block of Western Australia the Nevoria Mine was developed mainly in strongly deformed iron-formation (Williamson and Barr, 1965). The ore shoots are flat-lying quartz veins carrying much pyrrhotite and gold; some are interrupted by pegmatite dykes, but the exact age of the gold mineralization with respect to these dykes is not stated.

Some of the Precambrian gold-bearing sulphide lodes of the Kolar goldfield in India as described by Narayanaswami *et al.* (1960) may be in the sulphide facies of iron-formation. These are described as containing abundant graphite in places and grading into graphitic lodes (Fig. 26). The sulphide lodes are also marked by an abundance of pyrrhotite, a sulphide mineral that is particularly diagnostic of gold lodes in iron-formation.

The principal features of gold deposits in iron-formations can be summarized briefly. Nearly all deposits have an epigenetic aspect, that is the gold-bearing quartz stringers, lenses and irregular pods, the gold-bearing sulphide stringers and the massive sulphide lenses and irregular bodies are clearly in dilatant zones such as fractures, small faults, drag folds and contorted parts of the iron-formations.

In some deposits there is considerable evidence for replacement of the carbonate facies (siderite and dolomite) of the iron-formations by quartz, silicates, sulphides, etc. Most deposits are characterized by relatively marked amounts of pyrrhotite rather than pyrite, although the latter is usually present in the ores. Graphite is present in a number of deposits. The gold is intimately associated with the sulphides in many deposits and is rarely visible to the naked eye. The Au/Ag ratio in nearly all deposits is greater than 1. The grade of the deposits and occurrences ranges all the way from <0.01 to 0.5 oz Au/ton.

The source of the gold, silver and other elements such as arsenic and sulphur is probably the sedimentary beds comprising the iron-formations, particularly the graphitic sulphide facies and the pyritiferous chlorite facies. During metamorphism, granitization and injection of granitic bodies, dilatant zones appeared in competent beds of iron-formation, and these were filled with quartz, sulphides, gold, etc. extracted from the pile of sediments comprising the iron-formations and in places also from andesites, pyritiferous shales, pyritic tuffs, etc. Where carbonate facies constituted the bulk of the iron-formations replacement of the carbonates by diffusing constituents such as SiO_2, As, S, etc. predominated. More is said about these processes in the section on the origin of gold deposits at the end of this chapter.

Disseminated deposits in chemically favourable sedimentary beds

Gold deposits of this type occur mainly in carbonate-bearing rocks such as limestone, dolomite, calcareous quartzites and calcareous shales. They may be of any age, but the most productive to date are of Tertiary age. The orebodies are commonly irregular, but some are tabular following specific beds or series of beds. Most of the deposits occur in highly faulted terranes, and the orebodies generally spread out into beds laterally from faults or fractured zones. The replaced beds or series of beds are often disturbed but not generally highly brecciated or contorted. The mineralization is highly variable, but the development of quartz, pyrite, arsenopyrite, and small amounts of other sulphides and sulphosalts is universal. Silicification is the main process in their formation. The principal gold mineral in most of these deposits is the native metal, commonly low in silver. The native gold is usually widely disseminated through the deposits and is generally microscopic. Ore shoots usually have to be outlined by assay.

Numerous examples of this type of deposit occur throughout the world. Some of the replacement orebodies in dolomitic limestone and phyllitic quartzite of the Salsigne Gold Mine in France (Fig. 42) belong in this category. The protores of the Kuranakh type residual deposits in southern Yakutia, U.S.S.R. are also of this type (Fig. 70). The best known examples are in north-central Nevada, where four deposits – Getchell, Cortez, Carlin and Gold Acres – have been extensively investigated.

The literature on the Nevada disseminated deposits is extensive, the papers by Joralemon (1951), Hausen and Kerr (1968), Wells *et al.* (1969), Radtke and Scheiner (1970*a,b*), Wells (1971), Roberts *et al.* (1971) and Radtke and Dickson (1976) being particularly informative, especially the last, which includes an extensive bibliography.

The four deposits – Getchell, Cortez, Carlin and Gold Acres – differ in their general morphology but are remarkably similar in their mineralization and geochemistry. All are thought to be of Tertiary (Oligocene?) age. Silberman *et al.* (1974), however, state that Getchell has been dated at approximately 90 m.y., Gold Acres has a probable age of 92 to 94 m.y., Cortez is younger than 35 m.y., and the age of Carlin is uncertain. This suggests a broad range for the age of mineralization from late Mesozoic to middle Tertiary. The age of 80 m.y. for the Getchell Mine has been disputed by Joralemon (1975), who considers the deposit to be younger than 20 m.y. In a later discussion, however, Berger *et al.* (1975) maintain that the older age is most compatible with the geologic, geochemical and isotopic data available. The gold in the deposits is extremely fine grained (microscopic) in most parts of the deposits, and the Au/Ag-ratios range from 9 to 30. Such ratios are unusual but not unique for Tertiary deposits as witness the high ratios at Cripple Creek, Colorado (~12). The geochemistry of the various deposits is essentially similar. There has been widescale replacement of carbonates by silica which is manifest by a marked increase in the latter constituent in the orebodies and a decrease in CO_2 and some of the other constituents of the carbonates, especially calcium. Other elements introduced include Fe, Ba, As, Hg, Sb, Pb, Zn, Cu, W, Au, Ag and S. At Carlin and Cortez, Radtke and Scheiner (1970*a*) consider that carbonaceous matter played a large part in the precipitation of the gold from acid hydrothermal solutions at $175 \pm 25°C$. Subsequent oxidation of the gold-organic complexes so formed precipitated the gold in a microscopic form. Wells (1971) on the other hand, using electron microprobe methods, noted a close association of gold and arsenic with tiny grains of arsenic-bearing pyrite and no particular association with carbonaceous matter as suggested by Radtke and Scheiner (1970*a*).

The four disseminated deposits are spatially related to the Roberts Mountains Thrust Fault, the orebodies lying either within the thrust zone or within carbonate rocks a few hundred feet below it, especially where the thrust has been domed. Three prerequisites for ore are emphasized by Roberts *et al.* (1971), namely: (1) a source for gold-bearing solutions; (2) fractured and permeable ground to permit access of solutions; and (3) precipitants such as carbonate and/or organic carbon. Each of the deposits differs somewhat in structure and mineralogy and will be described briefly. Details should be sought in the references cited.

The gold orebodies in the Getchell deposit are sheetlike masses that lie along the various strands of the Getchell fault zone. They extend at least 7000 ft horizontally and 800 ft down the dip, varying in width from a few feet to more than 200, averaging about 40 ft. The ore is in sheared and mineralized argillite and limestone, granodiorite and andesite porphyry dykes cut by quartz, calcite and dolomite veins and containing a plastic 'gumbo' that is rich in gold. The 'gumbo' is evidently an alteration product of carbonaceous shale or argillite and chert. The mineralogy of the ores is low temperature, comprising quartz, gold, realgar, orpiment, stibnite, pyrite, marcasite, arsenopyrite and minor amounts of other sulphides. According to Silberman *et al.* (1974), K-Ar ages of the granodiorite, andesite, porphyry, tungsten-bearing tactites and altered granodiorite in or near the Getchell Mine indicate that emplacement, alteration and mineralization are all part of a magmatic-thermal episode that took place approximately 90 m.y. ago.

The Cortez deposit is mainly in altered calcareous siltstone and limestone of the Silurian Roberts Mountains Formation near an intrusive porphyry body (Fig. 58). No obvious structural feature controls the gold mineralization except perhaps the Roberts Mountains thrust. The hypogene mineralization comprises quartz, gold, pyrite and small amounts of other sulphides found in the other disseminated deposits. Based on hydrogen isotopic data Rye *et al.* (1974*b*) have concluded that the age of the mineralization in the Cortez deposit is Tertiary. They further concluded from hydrogen isotope data that meteoric water was the dominant component of the ore-forming fluids. The lead and sulphur isotopic data were considered to be consistent with the idea that the sulphur and gold were locally derived, probably from the Roberts Mountains Formation.

The gold orebodies of the Carlin deposit are in the upper part of the Roberts Mountains Formation, several hundred feet below the Roberts Mountains thrust (Fig. 59). The orebodies are diffuse irregular sheets that follow the stratigraphy of the carbonate beds but also cut across the bedding. In places a relationship to faults is evident. The mineralization comprises quartz, barite, realgar, pyrite, stibnite, cinnabar, sphalerite and galena in variable amounts. The gold is present as the native metal and as a gold-organic compound according to Roberts *et al.* (1971). Wells (1971) did not find the gold-organic compounds, however, using electron probe methods. Rather, he observed that most of the gold is associated with fine-grained arseniferous pyrite. In a recent contribution Harris and Radtke (1974) using statistical procedures have concluded that the paragenetic sequence at Carlin was probably: (1) early (?) barite; (2) disseminated quartz, pyrite, Au, Hg, As, Sb; (3) As, Sb, Hg sulphides, mainly as realgar, orpiment, stibnite and cinnabar accompanying late barite; and (4) overlapping Pb, Zn, Cu, Mo sulphides. They also observed that primary ores with low organic carbon contents show high correlations between the elements Au-Hg-As-Sb. In high carbon ores only Au to Hg show a high correlation reflecting the mutual associations between them and organic materials. Poor correlations within certain parts of the East and Main orebodies confirm the theory of a late superimposed As, Sb, Hg sulphide stage. Correlations among Au, Ba, Cu, Mo, Pb, Zn, in the West orebody are highest between base metals, followed by Ba to base metals and lowest between Au to base metals. Correlations between Au and Ba are consistently negative over the entire deposit, reflecting their paragenetic separation. B and W, present in anomalous amounts, together with Se and Te, which exhibit only very small concentrations in mineralized rocks, show exceedingly low correlations to each other and to Au. In a later publication Harris and Radtke (1976) have slightly modified the paragenetic sequence. They now consider most of the barite to be a late stage mineral. They also noted that linear regression analyses of gold with the independent variables boron, tellurium, selenium, tungsten suite showed that data for these elements fit a linear model poorly. The only significant

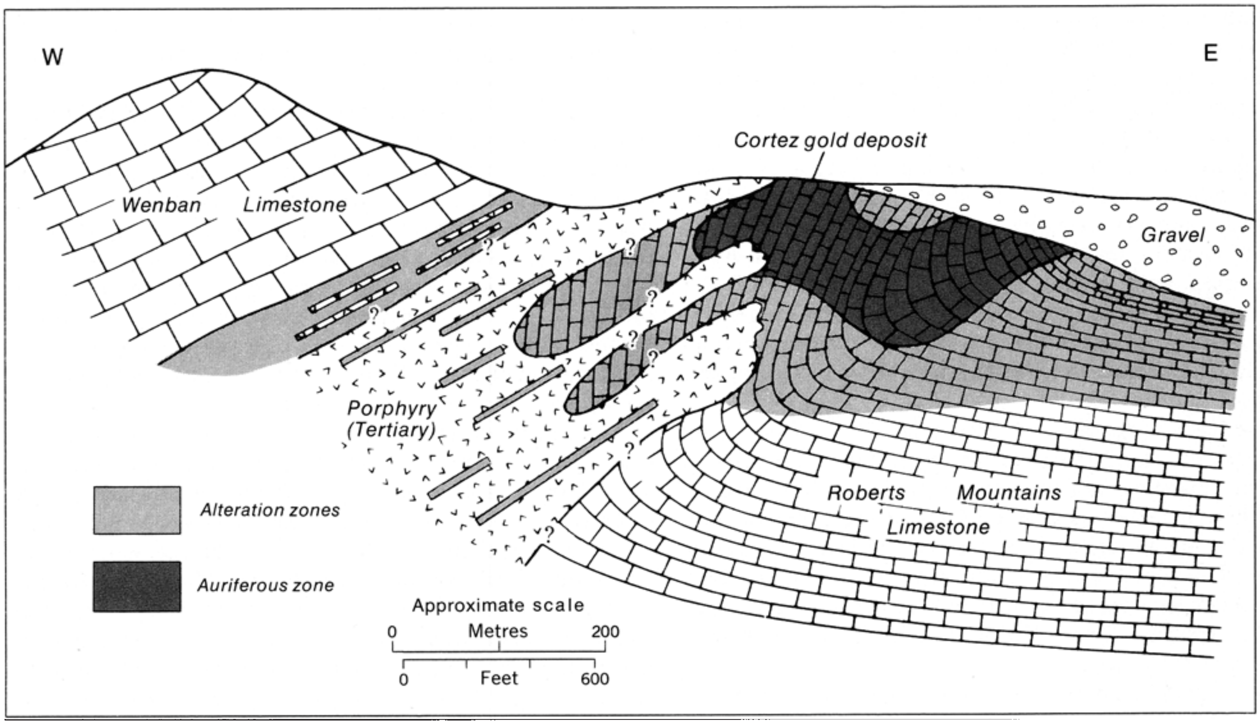

Figure 58. Idealized cross-section through the Cortez gold deposit from west to east showing rock units, gold deposit, alteration zones (the lower extent of which is unknown) and overlying gravels (after Wells *et al.*, 1969).

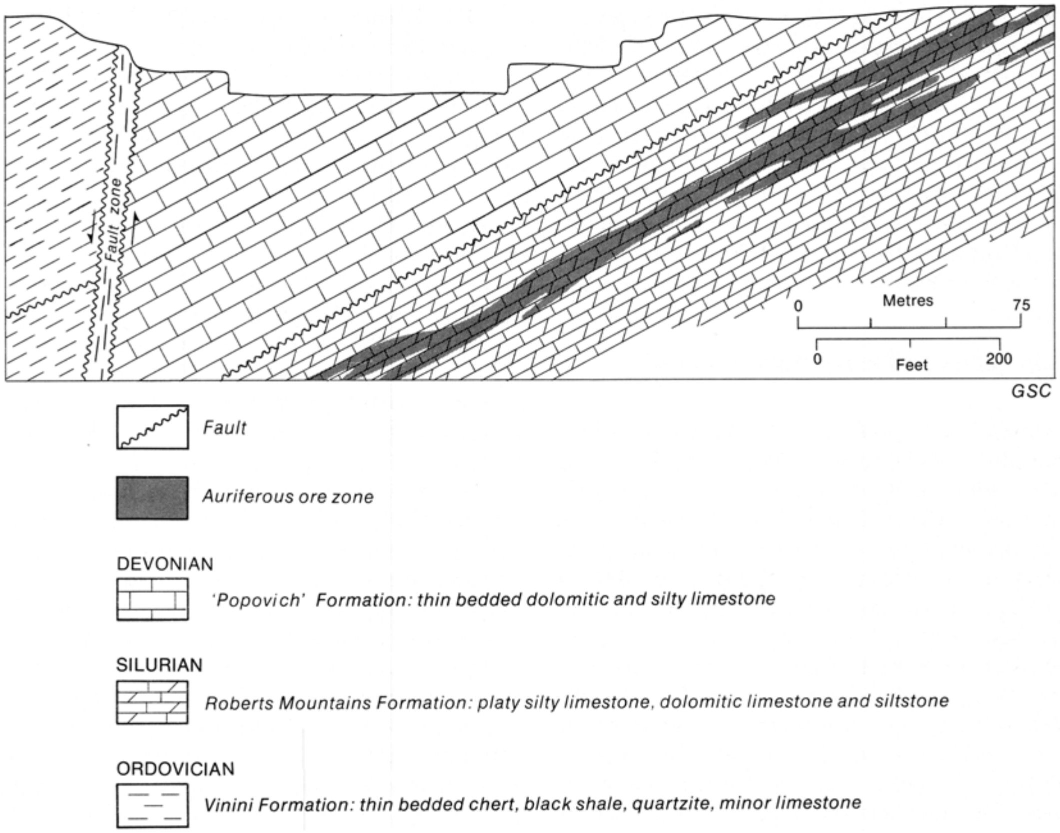

Figure 59. Cross-section of Carlin orebody, Carlin, Nevada (after Hausen and Kerr, 1968).

correlation found was between gold and tellurium; this correlation is strongest in the East orebody and becomes progressively weaker through the Main and West orebodies. The mode of tellurium occurrence was not firmly established, but the authors considered that tellurium and possibly, selenium could be present in hydrothermal pyrite or could coat pyrite grains together with gold, mercury, arsenic and antimony. Other details should be sought in the original paper.

The grade at the Carlin deposit ranges from 0.24 to 0.31 oz Au/ton according to the published reports.

The ore deposits at Gold Acres are in the brecciated zone of the Roberts Mountains thrust and in rocks above the thrust. The host rocks are sheared and brecciated chert, shale, limestone and altered felsitic intrusive rock. Tactite zones with pods and veinlets of pyrite, arsenopyrite, sphalerite, galena and low gold values are also present. Disseminated gold ore is erratically distributed within the thrust zone and along fracture zones and in felsite.

In a recent contribution Radtke and Dickson (1976) state that disseminated gold deposits of the Carlin type occur in many areas of the Basin and Range Province of the United States. The formation of these deposits, characterized by the elemental association, Au, As, Sb, Hg and Tl, was a part of the events that shaped the Basin and Range Province. Most deposits are located along the margins of ranges or near the interior of ranges along high-angle normal faults. They are not genetically related to thrust faults such as the Roberts Mountains thrust.

A deposit similar to that at Carlin in Nevada has recently been described by Richards *et al.* (1976) in Tertiary rocks in the Queen Charlotte Islands, British Columbia. This deposit (Specogna) is reported to contain an indicated reserve of more than 50 million tons averaging 0.06 oz/ton gold and 0.1 oz/ton silver. Other metallic elements present in anomalous amounts include Hg, As, Sb and Te. Possible major controls of mineralization include proximity to an unconformity, proximity to a major fault, and permeability of the host Skonun Formation of Miocene to Pliocene age. Quartz-feldspar porphyry dykes, although volumetrically insignificant, are thought to be important in the mineralizing process. Alteration effects include strong silica metasomatism, pervasive pyritization and intense clay alteration of feldspar in sandstones and in dykes. Although the gold mineralization is central to a much larger zone of silica, clay and pyrite, zoning of alteration is obscure. Dispersion of Hg in the rocks forms a halo about the better-grade gold. Other metallic elements form weak patterns being peripheral or central to the focus of mineralization.

Some brief remarks about disseminated gold deposits in chemically favourable rocks will serve to close this section. These deposits invariably have an epigenetic aspect and are most commonly developed in carbonate rocks in or near fault and fracture systems; commonly also near porphyry intrusions. Silicification is the predominant process in their formation. Most have been interpreted as being of low temperature hydrothermal origin. Thus, Radtke and Scheiner (1970*b*) postulated a low temperature (175±25°C) hydrothermal origin from acid solutions for the Carlin and Cortez deposits. The source of the gold and other constituents in the orebodies has not been considered in detail by any investigators studying these deposits, although a few allude to granitic rocks, porphyries, etc. as a possible source. It seems more probable that the pile of sediments in which these deposits occur is the source of the gold and other epigenetic elements, an hypothesis that should be tested in the areas where these deposits occur. Carbonates and possibly organic carbonaceous matter seem to have been the effective precipitants of silica, various sulphides and gold.

Gold deposits in quartz-pebble conglomerates and quartzites

These are the largest known gold deposits and have provided over 60 per cent of the world's gold production in the last 50 years. In addition some of these deposits contain economic quantities of uranium. Other deposits in this category are characterized by economic concentrations of uranium, thorium and rare-earths and only traces of gold and silver. There is an enormous amount of literature on these deposits, and no attempt will be made here to review any of it in any detail. While the deposits are remarkably similar in many respects, in detail there are numerous differences, some small and some major, that serve to stir up controversies about their origin. In fact, perhaps no metallic deposit has exercised the minds of economic geologists as regards origin as much as the gold-bearing quartz-pebble conglomerates since their discovery on the Witwatersrand of South Africa in 1886. By the mid-1940's the protracted controversies between the placerists, modified placerists and hydrothermalists had subsided, only to flare up again with renewed vigour and acrimony among a new generation when uranium was discovered or rediscovered in some of the deposits.

The general characteristics of these deposits will be dealt with first, some typical examples will be described briefly, and finally the various views on their origin will be outlined. Details about individual deposits or clusters of deposits are not given; these can be consulted in the references cited.

Quartz-pebble conglomerate deposits bearing gold, uranium, thorium and rare-earths are widely distributed. The best known examples are the Witwatersrand in South Africa, the Tarkwa conglomerates in Ghana, the Jacobina conglomerates in Brazil and the Elliot Lake–Blind River conglomerates in Ontario, Canada. In Rhodesia, gold-bearing conglomerates somewhat similar to those of the Rand occur in the Bulawayo area (Mennell, 1905). Some of these were worked for gold at the Eldorado Mine and elsewhere. The grade at the Eldorado Mine averaged 0.5 to 1 oz Au/ton or more. In Tanganyika near Tabora, a gold-bearing conglomerate has been explored, and in Zaire the Ruwe Mine, some 80 mi west of Kambove yielded both gold and platinum from (Permo-Triassic?) sandstones and quartzites. Old records indicate the grade at this mine to average about 10 ppm Au, 11 ppm Pt and 2 ppm Pd. Relatively little work seems to have been done on the last two conglomerates in recent years. Early reports and references are given in Emmons (1937). Numerous other occurrences of these types of conglomerate are known in Finland, U.S.S.R., Australia and elsewhere (Davidson, 1964–1965; Rozhkov and Pisemskey, 1966; Radkevich, 1966; Volodin, 1966; Nozhkin *et al.*, 1972; Pisemskii and Pletnev, 1972; Andrade Ramos and Fraenkel, 1974; Robertson, 1974).

The productive quartz-pebble conglomerate deposits are all of Precambrian age. Phanerozic examples are known, but none of these have yet proven to be of economic interest. The details of the ages of the Precambrian quartz-pebble conglomerates are not entirely clear. If we can believe the isotopic dating, the Witwatersrand deposits are 2.3 to 2.8 billion years old, the Blind River–Elliot Lake deposits (usually considered as Aphebian in age) 2.3 to 2.5 billion years and the Jacobina 2.5 billion years. According to some age scales this places at least some of the deposits well into the Archean. Stratigraphically speaking, however, all of these deposits lie on old basement rocks (greenstones, greywacke, slate, gneisses, schists, granites, etc.) that have been traditionally referred to as Archean in many countries. The absolute ages of the deposits does not really concern us here, and we shall not consider the problems further. The superincumbent stratigraphic relationship of the conglomerate deposits to the older (Archean) rocks, which throughout the world contain a great variety of epigenetic gold deposits, deposited before the conglomerates were laid down, is important.

The mineralized quartz-pebble conglomerates commonly occur as interbedded thin beds and elongated lenses in thick sedimentary sequences composed of clastic sediments, mainly quartzites, grits and microconglomerates with some hydrolysates, principally shales. Commonly the conglomerates are restricted to specific members and not scattered indiscriminately throughout the sedimentary sequence. In some sequences (e.g., Witwatersrand, Ventersdorp System) volcanic rocks are present, generally near the top of the stratigraphic section. The ore-bearing conglomerate beds or sequences of beds vary greatly in thickness, but most are only a few feet thick; ore-bearing horizons thicker than 10 ft are uncommon; some of the richest conglomerate beds are only inches thick. In some districts the mineralized conglomerate beds and conglomerate horizons are particularly persistent, extending for tens and even hundreds of miles.

The quartzites, shales and argillites in the sedimentary sequence appear in most places to be relatively normal for these types of rocks. The quartzites generally consist essentially of quartz grains, feldspar, small chert fragments, sericite, chlorite, pyrophyllite in places and chloritoid. The shales and argillites are similarly constituted but with much less quartz and more micas. Some of the shales and argillaceous quartzites are red due to the presence of hematite. Others carry magnetite. The quartzites generally exhibit a moderate degree of crossbedding, a feature that is relatively uncommon in the conglomerates, although in some deposits rude crossbedding is present in these coarse rocks. The shales are seldom highly graphitic, although examples of carbonaceous shales and conglomerates are known in the Black Reef in the Witwatersrand Basin. In both the quartzites and conglomerates erosion channels and 'cut and fill' structures are present but are not a marked feature in most districts. Ripple marks are present on the shales and quartzites of some districts.

The origin of the conglomerates and their associated sediments has been variously interpreted by a host of sedimentary experts, few of whom seem to agree on either the major or minor details. A whole spectrum of broad origins has been suggested including terrestrial, littoral and marine. Among these, deposition in alluvial fans, on piedmonts and flood plains of large rivers, in enclosed basins, in large deltas, along marine shorelines and on gently sloping continental shelves have all had their proponents. Normal weathering and erosion processes, sometimes drastic, have appealed to many as the agency producing the sedimentary materials, but some have invoked glaciation followed by sedimentary milling and winnowing of the products as the responsible mechanism. Particularly perplexing to many theorists is how persistent beds of thin oligomictic conglomerates (sheet gravels) could have accumulated over such vast areas. One constantly wonders whether these conglomerates and their associated sediments, and indeed most Precambrian sediments, can be interpreted in terms of uniformitarian principles.

The paleoclimatic conditions under which the quartz-pebble conglomerates and their associated quartzites were laid down can only be conjectured. These rocks suggest intensive weathering, erosion and sedimentary milling. Intensive weathering infers the presence of considerable amounts of oxygen, carbon dioxide and water in the paleoatmosphere. There is little doubt that the last two compounds were present since the conglomerates and quartzites were water lain, and volcanism in Archean times produced abundant carbon dioxide (Boyle, 1976*a*), much of which was probably carried over into the Proterozoic atmosphere to persist through various cyclic processes to the present day, being augmented from time to time during younger periods of volcanism. The availability of oxygen during early Proterozoic time has, however, been questioned, a number of investigators claiming that the quartz-pebble conglomerates were laid down under anoxogenic conditions. This appears improbable since hematitic iron-formations are relatively abundant in the Archean and that molecular oxygen was probably one of the gaseous products of the early earth, its origin being due to radiolysis and other early geochemical processes (Boyle, 1976*a*). There is a strong possibility that the quartz-pebble conglomerates and quartzites of Proterozoic age represent well winnowed accumulations of quartz and micas from glacial tills, in which case the weathering and erosion were essentially mechanical. This is suggested by the fact that the Aphebian (Lower Proterozoic) is marked by glacial periods, the tillites of the Gowganda Formation and the Witwatersrand (Wiebols, 1955) being manifestations. Having regard to these speculations it seems probable that the Proterozoic quartz-pebble conglomerates and their associated quartzites were deposited during a warming postglacial period under an atmosphere with a relatively high oxygen content.

The detailed constitution of the conglomerates is remarkably similar, but there are a few marked differences between certain deposits. The pebbles in nearly all of the ore-bearing conglomerates are predominantly quartz with occasional occurrences of chert, quartzite, porphyry and slate. Other types of pebbles are rare according to the literature and this writer's examination of the Elliot Lake–Blind River deposits and samples from other deposits in many parts of the world. The quartz and other pebbles exhibit a relatively high degree of sorting in most deposits and show evidence of thorough abrasion, two features suggesting extensive travel or long sedimentary milling. Initially, most of the pebbles were probably well-rounded, but in many deposits they show flattening and roughly ellipsoidal forms. Some resemble large almonds hence the name 'banket', which is Dutch for almond layer cake. The flattening and stretching of the pebbles is evidently due to tectonic activity during the folding and metamorphism of the beds. The bulk of the matrix of the conglomerates is composed essentially of fine-grained quartz, sericite, chlorite, chloritoid and minor amounts of a variety of other minerals which need not concern us at this point. In some of the Witwatersrand conglomerates, pyrophyllite is relatively abundant (Liebenberg, 1955).

With respect to iron minerals there are two types of conglomerate deposits – those containing pyrite and pyrrhotite and those with hematite or more rarely ilmenite or magnetite. The iron sulphides and oxides seem to be mutually exclusive in the conglomerates of particular fields. Iron oxides are absent or extremely rare in the conglomerates of the Witwatersrand, Jacobina and Blind River–Elliot Lake deposits, and pyrite and pyrrhotite are rare in the Tarkwa conglomerates. It is interesting, however, that some of the interbedded shales in the Rand and the other fields commonly carry considerable amounts of magnetite. Conglomerates rich in pyrite and pyrrhotite carry uranium, thorium and rare-earths; those with the iron oxides do not carry these elements in more than trace amounts in the deposits known to date. The pyrite in the conglomerates is predominantly of two types – a rounded 'buckshot' type and an euhedral to subhedral type. These types have been variously interpreted as detrital or formed during or after sedimentation by a number of processes. Some pyrite occurs in veinlets and fracture fillings and is obviously epigenetic. The hematite in the Tarkwa deposits is present mainly as grains that do not appear to be detrital in their present form. They seem to be more like crystallized grains derived from a chemical precipitate. More will be said about the iron minerals in the descriptions of the principal deposits, but it should perhaps be mentioned here that Robertson (1974) places considerable emphasis on the point that all of the uraniferous quartz-pebble conglomerates are younger than the first Proterozoic red beds, a feature that he thinks points to an anoxygenic atmosphere for the earth during the sedimentary deposition of detrital uraninite in the quartz-pebble conglomerates. This view is open to serious doubt not only because of the existence of the hematitic Tarkwa deposits but also because of the presence of abundant iron-formations (Algoman-type) in the Archean, a fact that strongly indicates that oxygen was relatively abundant in the very early atmosphere (Boyle, 1976*a*).

The above description covers the principal components of the quartz-pebble conglomerate deposits. Those of economic interest, however, commonly contain a number of base metal sulphides, uraninite, brannerite, solid hydrocarbons, platinoids and other minerals in addition to gold. These constituents are best described in the context of specific deposits where the details are more meaningful.

The source of the most abundant and specific components of the conglomerates and their associated sediments is a difficult problem, in some areas probably insoluble, because the source rocks have been either completely removed by erosion or deeply buried by younger rocks. There is evidence in some regions such as the Rand, Jacobina and Tarkwa for an Archean hinterland marked by the presence of gold-quartz deposits, gneisses and granitic rocks, the last two a possible source of uranium, thorium and rare-earths. In other regions such as Blind River–Elliot Lake the hinterland appears to have been mainly granitic gneisses, intrusive granitic bodies and only minor belts containing gold-quartz deposits. This difference may partly account for the general paucity of gold in the Blind River–Elliot Lake ores.

The precise source of the quartz in the quartz pebbles and matrix of the conglomerates is an interesting problem. All investigators agree that the pebbles are vein quartz, but few specify from what type of veins the quartz was derived. Pretorius (1964), describing the vein quartz pebbles in the Central Rand conglomerates, mentions the spectrum of colours present, including white, cream, grey, mottled grey and black, jet black, opalescent blue and emerald green, the last relatively rare. These colours are typical of nearly all quartz-pebble conglomerates throughout the world. The writer has examined the macroscopic and microscopic characteristics of the quartz pebbles and matrix quartz from various quartz-pebble conglomerate deposits from various parts of the world in an attempt to relate the quartz to Archean deposits of the mineral. He concludes that the white to milky variety of quartz in a number of the deposits is essentially similar to quartz present in many of the gold-quartz veins in greenstones and Archean sediments. Many of the white quartz pebbles in a number of the deposits also match the so-called barren 'bull quartz' commonly present in volcanics and sediments in Archean gold belts. Some of the glassy colourless to white varieties of quartz pebbles in some deposits resembles pegmatitic quartz and were probably derived from these granitic bodies. The grey, mottled grey and black, and jet black varieties of quartz pebbles are characteristic of Archean gold deposits as mentioned in a previous section. These varieties of quartz could be derived from deposits either in greenstones or sediments. The opalescent blue to dusky blue quartz can be matched with that present in certain gold deposits in Archean greywackes and graphitic slates. The dark colour of some of the quartz requires comment. Part of the colour in some cases may be due to radioactivity (electronic darkening) associated with uranium and thorium now present in the conglomerates. Alternatively the quartz may have been initially or partly darkened in radioactive pegmatites. The latter appears the least probable since many of the quartz pebbles carry a dark outer border, which appears to have been induced in situ. Horwood (1917), the first geologist to investigate the black-edged pebbles, included illustrations of many fine examples of the phenomenon in his book on the Witwatersrand; the phenomenon is also notable in the Elliot Lake deposits, particularly in some of the ore shoots of the Denison Mine.

One of the striking features about the quartz pebbles is their general lack of original particles of gold, sulphides, uraninite, etc. Where these minerals are present in the quartz pebbles, they are obviously of secondary origin, since they commonly cut both the matrix and the pebbles or show undoubted replacement textures. These features have been repeatedly mentioned in the literature and are generally accepted by most investigators. Along the same line the writer has noted that the quartz pebbles do not generally show the marked cataclastic features of many gold-quartz veins. How are these features to be explained? The answer appears to lie in the extreme weathering and sedimentary milling conditions that the pebbles have endured. In the weathering and disintegration of gold-quartz veins containing sulphides the writer has noted that the vein quartz tends to disaggregate first along the seams and zones bearing sulphides, gold and carbonates and finally along the zones of cataclasis cemented by secondary quartz, carbonates, sericite, etc. The final product is dominantly quartz practically free of any other mineral, particularly gold and pyrite, and relatively free of abundant zones, seams and patches of cataclasis. Quartz of this type appears first in eluvial placers and ultimately in alluvial placers. The 'White Channel' gravels of the Klondike in Yukon, Canada are a case in point. Careful examination by the writer of the white quartz pebbles, which constitute a large proportion of these gravels, revealed only a few pebbles with pyrite and other sulphides and none with visible gold. Examination of numerous gold concentrates from these gravels and indeed from others in various placers in Yukon, British Columbia and elsewhere in Canada revealed only rare nuggets or pieces of gold with attached quartz gangue or pyrite. These observations agree with the observations of many investigators of gold placers as described in the literature for the last 70 years. It is thus evident that vein quartz and gold generally part intimate company but retain their general association during weathering processes and placer accumulation. This probably accounts for the fact that the quartz pebbles in the quartz-pebble conglomerates rarely contain gold or sulphides that can be proven to be of primary origin.

The source and manner of formation of the matrix of the conglomerates is of interest with respect to the origin of certain elements of a hydrolysate nature as will be mentioned later in the discussion on origin. Microscopic examination suggests that the quartz in the matrix is probably only partly detrital, a large part having been initially present in a dissolved or colloidal state. The same is probably true of the components that now constitute sericite, chlorite, chloritoid and pyrophyllite. Regardless of whether these observations are valid or not, there is no doubt that the matrix of both the conglomerates and their associated quartzites has undergone thorough compaction, cementation and reconstitution leaving minerals characteristic of the sericite-chlorite facies of metamorphism.

Krendelev *et al.* (1970) make reference to a number of the features just mentioned in their extensive study of sulphide-bearing quartz-pebble conglomerates of many types from various parts of the world. They note a general reconstitution of the matrix of these conglomerates and claim that even the quartz pebbles are often fully recrystallized in some deposits. They investigated gas-fluid inclusions in the quartz for their gaseous content and homogenization temperatures. They concluded that the gold and uraniferous ores in Precambrian sulphide-bearing conglomerates resulted from the activity of solutions with temperatures about 220–400°C and containing gases such as CO_2, O_2 and NH_3 (Rand).

One other general feature of the mineralized quartz-pebble conglomerates that requires mention is the common presence both in the conglomerates and their associated rocks of mineralized gash veins, fractures and faults. In the Rand many of the gash veins are filled with quartz, sulphides and gold. In the Blind River–Elliot Lake area the faults and fractures contain thucholite and sulphides. Elsewhere, these mineralized veins and fractures are present in or near the quartz-pebble conglomerate deposits but have not been described in detail. The origin of these mineralized structures and their relationship to the mineralized conglomerates has led to much controversy, a brief outline of which is given below.

Witwatersrand Basin, South Africa

The Witwatersrand, or more simply the Rand as it is generally called, was discovered in 1886; since then its many mines have produced more than 1 billion oz Au, 100 million oz Ag, considerable uranium and some platinoids. The annual production is about 30 million oz Au/year making the Rand the largest producer of the precious metal by far in the world. Some of its mines are the deepest in the world exceeding 10 000 ft in places. The reserves of ore averaging 0.1 to 0.3 oz Au/ton are said to be large.

The literature on the geology, mineralogy and geochemistry of the Witwatersrand is voluminous. An extensive bibliography covering the years up to 1959 has been compiled by Hargraves and Winter (1964) to which the interested reader is referred. Later references of interest are mentioned in the text that follows. The definitive textbook on the Rand is that edited by Haughton (1964*a*) in which the papers by Borchers (1964) and Brock and Pretorius (1964*a*,*b*) provide excellent summaries of the history, exploration, geology and mineralization of this unique goldfield. There is a recent review of the problems of the origin of the Rand by Pretorius (1975).

The Witwatersrand Basin, some 250 mi long and 90 mi wide, lies southwest of Johannesburg and has major orebodies along its northeastern, eastern, western and southern edges (Fig. 60). The general structure of the basin is a synclinal trough with peripheral faults in places and extensive cross faults in others.[24] The rocks of particular economic interest are all sediments of Precambrian age resting on a basement of granite, gneiss and schists. The generalized geological column for the basin is given in Table 61. The various systems are fairly readily correlated throughout the Rand Basin; correlation of the various individual reefs and reef systems from area to area is relatively difficult because of the discontinuous and lenselike nature of the reefs. The geological history of the basin is complex, involving several stages of extensive sedimentation and volcanic activity; only a brief outline of the salient features will be attempted here.

The oldest rocks, the Swaziland System, underlying the basin are Precambrian amphibolites, schists and gneisses intruded by or granitized to a variety of granitic rocks. Rocks equivalent to these in South Africa (Barberton Mountain Land), Rhodesia and elsewhere in Africa are the hosts for a variety of gold-quartz deposits. On the deeply eroded surface of the basement complex the Dominion Reef System, some 3000 ft thick, was laid down apparently only in some areas. The upper part of this system is composed of lavas, a lower sequence of amygdaloidal andesites followed upwards by felsite and rhyolite; the lower part of the system, some 300 ft thick, comprises grits, quartzites and conglomerates. The auriferous-uraniferous Dominion Reef conglomerates at or near the base have been worked in the Klerksdorp area. The Dominion Reef System was extensively folded before the deposition of the Witwatersrand System.

Unconformably overlying the Dominion Reef System, where it is present, and the basement complex generally is the Witwatersrand System, which is divisible into Lower and Upper divisions. The generalized stratigraphic column of both these divisions is given in Table 62. The Lower Division consists mainly of shales, quartzites, grits and conglomerates, only two of the last being sufficiently auriferous to be mined (Government Reef, and reefs in the Jeppestown Series in the Klerksdorp area). The Upper Division comprises mainly quartzites and conglomerates with minor shale. This division contains the most productive auriferous and uraniferous conglomerates of the Rand, including the Main-Bird Series, the Kimberley Reefs and the less persistent but payable Elsburg Reefs.

After deposition of the Upper Division of the Witwatersrand System there followed a major volcanic period during which lavas of dominantly basaltic to andesitic composition, quartz porphyries and felsites with minor intercalated banded tuffs, shales, cherts and breccias of the Ventersdorp System were laid down. Near the base in some areas there are quartzites, grits and conglomerates. The system varies greatly in thickness, exceeding 10 000 ft in some districts of the Orange Free State. The auriferous Ventersdorp Contact Reef lies at the base of the system and is mined on the West Wits Line, in the West Rand areas, and at one mine in the Klerksdorp area. It is generally assumed that the folded and eroded beds of the Witwatersrand System were the source of the gold and pebbles of this reef.

Following the outpouring of the Ventersdorp lavas, sedimentary and volcanic members of the Transvaal and Karroo systems were laid down; the latter now covers more than half of the Witwatersrand Basin. The Transvaal System is of interest since the Black Reef lies in quartzites, conglomerates and carbonaceous shales at the base. This reef occurs as conglomerate or channel fill and transgresses rocks of the Basement Complex, Witwatersrand System and Ventersdorp System. Gold values tend to be erratic, and uranium values are consistently poorer than in the underlying reefs. It is mined in the Klerksdorp, West Wits, West Rand, Central and East Rand areas. Some geologists consider that the gold and other minerals in the Black Reef represent the redistribution products of eroded reefs in the Upper Division of the Witwatersrand System.

The dip of the sediments and volcanics in the Rand Basin is variable as might be expected for rocks covering such a large area. In general the dips are less than 45°. Locally they may be very steep and even overturned as in the region of the peripheral faults of the basin and the Vredefort Dome.

Igneous bodies of several ages penetrate the rocks of the Witwatersrand Basin. Most of these are sills and steeply dipping dykes of basic and intermediate composition related to the Ventersdorp, Bushveld Complex and Karroo periods. Most of the rocks comprising the sedimentary pile of the Witwatersrand Basin fall into the greenschist (sericite-chlorite)

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[24] The synclinal trough idea may require modification as further work proceeds. Folding of a complex nature may account for the configuration of the Witwatersrand basin according to Dr. D. A. Pretorius (lecture, Ottawa, October 2, 1973).

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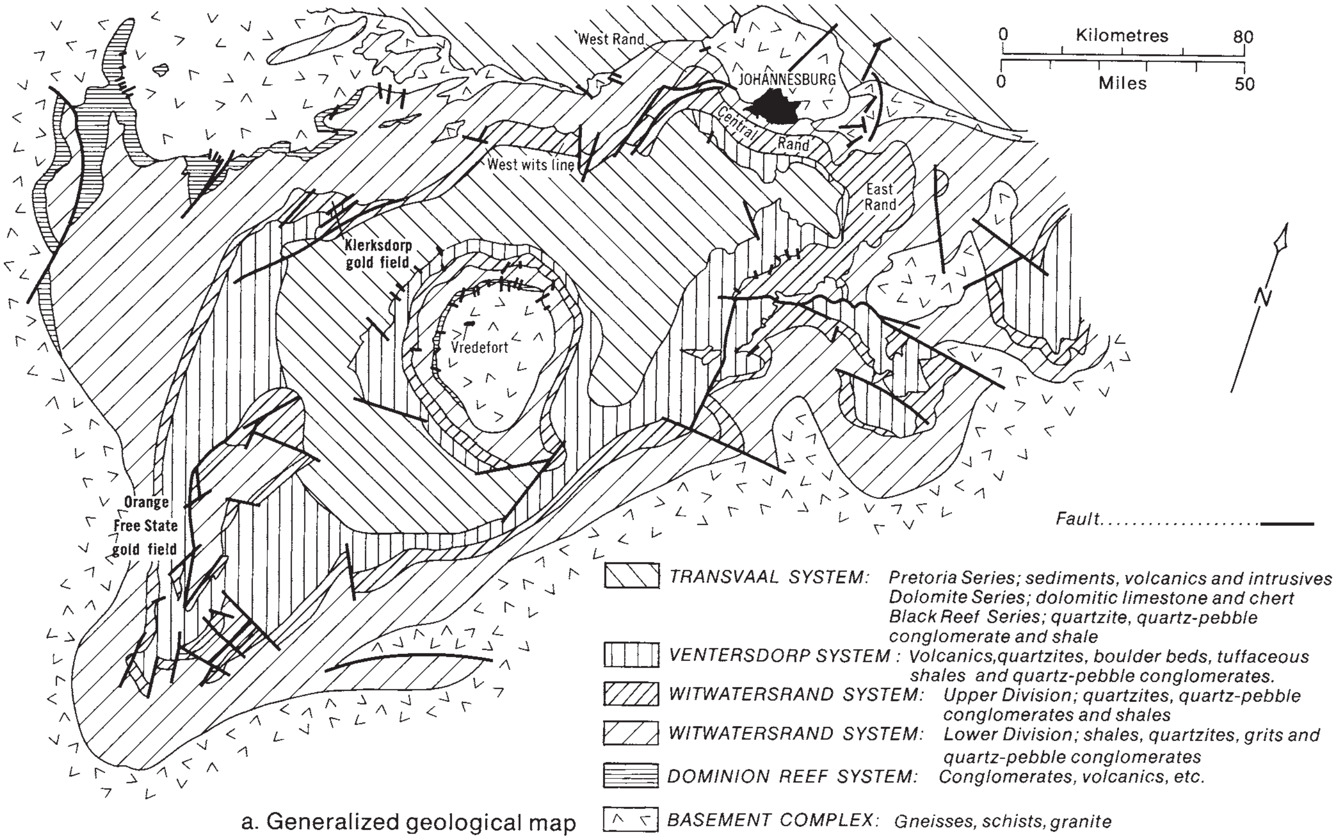
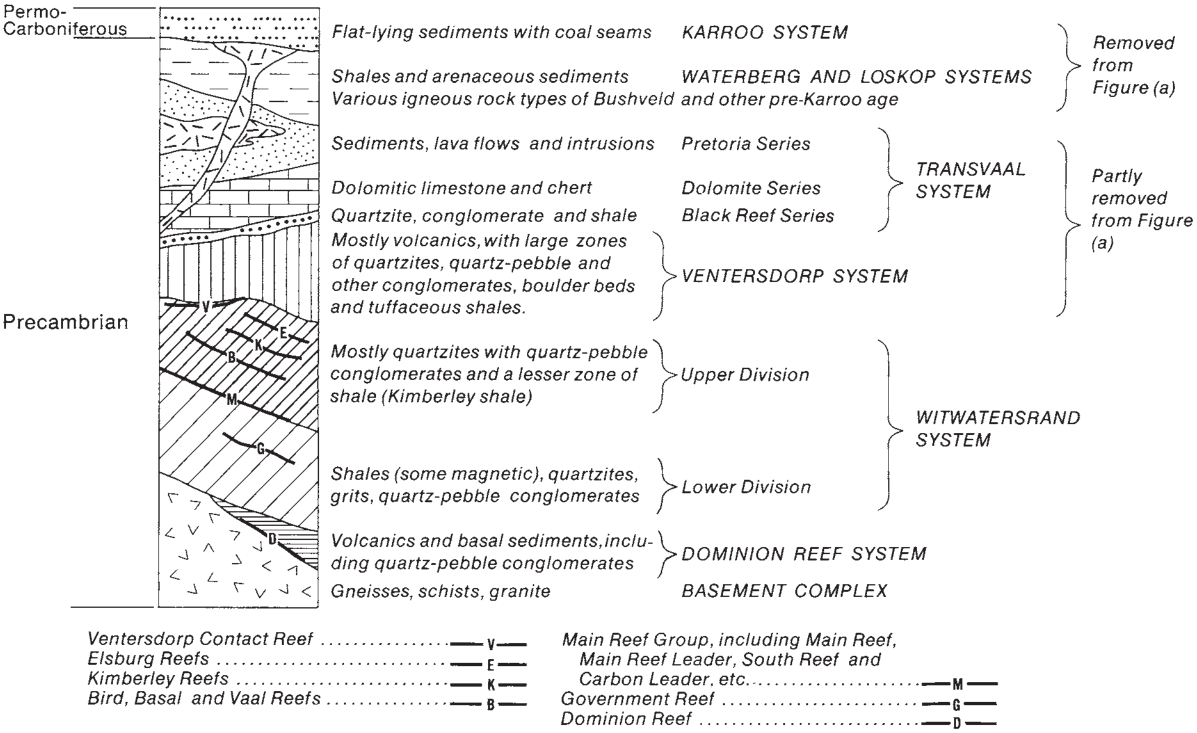


a. Generalized geological map



b. Generalized geological column

Figure 60. (a) Generalized geological map of the distribution of the Witwatersrand System beneath the younger covering rocks (after Borchers, 1964; Koppel and Saager, 1974; and others). (b) Generalized geological column showing the various geological relationships in the Witwatersrand Basin (after Borchers, 1964; and others).

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Table 61. Generalized geological column, Witwatersrand Basin, South Africa

	System		Lithology and remarks
Permo-carboniferous	Karroo System		Flat lying shales, grits, sandstones, etc. with coal seams
			Unconformity
Precambrian	Transvaal System		Shales, quartzites, dolomite, chert, conglomerate, lava flows, etc. Black Reef at base
			Unconformity
	Ventersdorp System		Mainly andesitic and basaltic lavas with porphyries, felsites, tuffs, shales, cherts and breccia some quartzites and conglomerates. Ventersdorp Contact Reef at base
			Conformity in some areas; unconformity in others
	Witwatersrand System	Upper Division	Mostly quartzites and conglomerates, and minor shale. Contains the auriferous Elsburg, Kimberley, Bird and Main Reef groups
			Conformity in places; unconformity in others
		Lower Division	Amygdaloidal lava at top, tuff, shales, quartzites, grits, conglomerate. Contains the auriferous Government Reef and other gold-bearing reefs near the middle of the division
			Unconformity
	Dominion Reef System		Conglomerate, quartzite, grit, arkose, amygdaloidal andesites, felsites and rhyolite. Auriferous Dominion Reef at base
			Great unconformity
	Swaziland System (Basement rocks)		Amphibolites, actinolite and hornblende schists, talc schists, serpentinites, gneisses and intrusive granitic rocks

Table 62. Generalized stratigraphical column for the Witwatersrand System in the Central Rand

Division and total thickness	Series and total thickness	Main stratigraphical marker horizons	Thickness of marker horizons
	(ft)		(ft)
Upper division Witwatersrand System (9400) Mainly quartzites and conglomerates with minor shale	Kimberley-Elsburg Series 6100	Elsburg Reefs	1500
		Kimberley Reefs	600
		Kimberley Shales	550
	Main-Bird Series 3300	Bird Reef Marker	100
		Bird Reefs	300
		Main Reef Group	100
Lower division Witwatersrand System (15 200) Mainly shales, quartzites, grits, and conglomerates	Jeppestown Series 3800	Jeppestown Amygdaloid	100
	Government Reef Series 6100	Government Reef	5
		Coronation Reef	5
		Coronation (or West Rand) Shales	500
		Promise Reef	5
	Hospital Hill Series 5300	Hospital Hill Quartzites	1300
		Contorted Bed	150
		Speckled Bed	5
		Ripple-marked Quartzites	20
		Water Tower Slates	800
		Orange Grove Quartzites	550

Source: Brock and Pretorius (1964*b*).

facies of regional metamorphism. The thermal effect of the various igneous bodies is local and overall minimal.

The rocks of the Witwatersrand Basin have suffered several periods of tilting, subsidence and erosion followed at the end of the Transvaal period by extensive folding and thrusting. In the centre of the basin the basement was thrust up, doming and in places overturning the overlying sediments to give a pronounced structure known as the Vredefort Dome. The sediments have been partly eroded from the top of the dome thus exposing a concentric pattern of outcrop of the rocks of the Witwatersrand, Ventersdorp and Transvaal systems. The idealized outcrop pattern of the Witwatersrand System, as well as the other systems, as shown by Borchers (1964) is an outer elliptical annulus of rocks dipping inward with low to moderate dips and a more or less circular annulus of rocks in the centre having variable dips. Extensive, and in places intricate, fault systems disrupt this ideal pattern throughout the basin.

The environment of deposition of the sediments and volcanics of the Witwatersrand Basin has been the subject of much discussion, and a number of hypotheses have been proposed including; the littoral (marine shoreline) hypothesis (Young, 1917); the sea floor hypothesis involving cyclothem deposition (Sharpe, 1949) or littoral source of pebbles (Graton, 1930); the deltaic or estuarine hypothesis (Mellor, 1916); the pediment hypothesis with a desert connotation (Antrobus, 1956); the alluvial hypothesis with deposition on a piedmont, flood plain or region of alluvial fans associated with large rivers and their tributaries (Reinecke, 1930; Bain, 1960); and the glacial hypothesis (Wiebols, 1955) involving the winnowing and sedimentation of materials from extensive till sheets and other glacial deposits. Brock and Pretorius (1964*a*)

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combine a number of these concepts into a four-delta hypothesis, the sedimentary materials being derived from a hinterland of red granite with inset synclines of gold-bearing Archean schists undergoing continuous uplift along a fault at the periphery of the basin. Sedimentary milling of the weathered products along the littoral zone is envisaged followed by movement and sedimentation of pebbles and other materials along the sea floor by wave-bottom effects assisted by gravity (Fig. 61).

In a more recent contribution to the problem of the depositional conditions that produced the Witwatersrand Pretorius (1975) attempts to resolve the various problems that have arisen since the 1964 synthesis. His remarks about this famous goldfield deserve to be quoted in full:

> It would now appear that the Witwatersrand depository was an intermontane, intracratonic, yoked basin with a fault-bounded northwestern edge and a gently downwarping more passive southeastern boundary. The enclosed basin was at least 350 km long in an east-northeasterly direction, and 200 km wide in a north-northwesterly direction. The structural environment resembled that of the Basin and Range Province, but a far wetter climate prevailed. The basin was a shallow-water lake or inland sea, no connexion to an open ocean having yet been found. The depository became structurally more unstable with time, and a pattern of interference folding produced structural depressions and culminations both on the rim and within the depository. The various goldfields developed in downwarps between basement domes. The northwestern side was episodically but continuously rising, causing the basin-edge to advance progressively farther towards the depositional axis. The final depository was smaller than the original, so that, overall, the sediments were laid down in a shrinking basin. Conditions were generally transgressive in the Lower Witwatersrand Division and generally regressive in the Upper Division. Second-order transgressions and regressions were superimposed on these primary trends. Between the base of the Lower Division and the base of the Upper Division, the edge of the basin moved southeastwards by 60 km, and the depositional axis by about 10 km.
>
> A high-energy transfer system from the source to the depository took the form of a relatively short, linear fluvial array. From the areal geometry of the different stratigraphic horizons, the patterns of facies variations, the trends in the changes of grain-sizes of sediments, the directions and patterns of paleoflow, the nature of the environmental indicators, and the distribution of heavy minerals, it would appear that a goldfield is a fluvial fan or fan-delta that was formed where the river system debouched into the lake via a canyon cut through the high ground to the northwest of the peripheral faults. In this type of environment, there were far greater amounts of water on a typical alluvial fan and the energy-level was higher than that on an oceanic delta. After emerging from the canyons, the rivers flowed short distances over a piedmont plain and then dispersed through a braided-stream pattern into the basin. The fluvial fans were restricted to the northwestern margin of the depository, and some of them coalesced in their more distal parts, leading to the impression of extensive sheets of uniform gravel. The largest of the fans was that constituting the East Rand goldfield, which measured 40 km in length down the central section from the apex to the fanbase, 50 km wide in width in the midfan section, and 90 km in width in the fanbase section. The western margin of this fan was 45 km long and the eastern flank 60 km. Six fluvial fans have so far been discovered – those constituting the Orange Free State, Klerksdorp, West Wits, West Rand, East Rand, and Evander goldfields. The original Central Rand, on which the Main Reef conglomerates were discovered, would seem to be a geographical entity only, since, geologically, it represents the coalescence of the eastern part of the West Rand fan and the western part of the East Rand fan.
>
> The gold and uranium mineralization has been recognized to occur in five forms: (i) in the matrices of the conglomerates, (ii) in heavily pyritic sands filling erosion channels, (iii) on quartzites along a plane of unconformity between successive cycles of sedimentation, (iv) on shales along planes of unconformity, and (v) in carbon seams on, or adjacent to, planes of unconformity. The three last-mentioned types of reefs were formed in the terminal stages of one cycle of sedimentation, and the first-mentioned two in the initial stages of a succeeding cycle. The gold and uranium were transported as detrital particles and in solution as chloride- and cyanide-complexes. Concentration took place physically, through gravity settling and subsequent winnowing by wave- and current-action, and biochemically through interaction between the gold and uranium and the algal or lichen colonies that preferentially developed about the mouths of the major rivers, in the quieter water conditions on the margins and fanbases of the fluvial fans, and at the end of certain cycles of sedimentation.
>
> The conceptual model of a typical Witwatersrand goldfield is portrayed in Figure 62 (this volume). The apex of the fluvial fan was located along the tectonically unstable basin-edge where repeated uplift of the source-area side took place along longitudinal faults. The fanheads of earlier fans were thus uplifted and reworked into later fans, while the midfan and fanbase sections were structurally depressed and thereby preserved. The downward displacement of the midfan and fanbase also caused transgression of the lake waters, producing winnowing of the fines and lag concentrations of the heavier minerals. Longshore currents moved the finer sediments farther away from the entry-points to form asymmetrical fans owing to the clockwise movement of the water in the depository. The typical fluvial fan had two main lobes in which were located a larger number of braided-stream channels, thicker and coarser clastic sediments, and higher concentrations of detrital gold and uranium. The material that was laid down between the lobes took the form of sands, silts, and muds, similar to that which accumulated on the fan margins and base. Conditions under these lower-energy regimes at times provided the optimum environment for the growth of algae or lichens, which took the form of thin algal mats. The gold was of too fine a grain to settle in the fanhead facies. The highest concentrations took place in the midfan lobes, with the peak of uranium mineralization a little farther down the slope than the peak of the gold. The energy-level dropped too low to permit the transportation of detrital gold to the fanbase section. However, the gold and uranium that were in solution did interact with the biogenic material that was present in the low-energy environments.
>
> A fluvial fan was built up in a series of pulses of sedimentation, which started with progradation during regression, went through aggradation during transgression, and ended with degradation during stillstand. These three stages constituted a single cycle of sedimentation. A new cycle was initiated through tectonic adjustment along the longitudinal faults. Such adjustment produced a steepening of the paleoslope, with the result that the increased competency of the streams brought greater amounts of coarse debris onto the fan. The higher energy-level caused progradation and a consequent regressive relationship with the earlier sediments. The first pulse laid down an openwork gravel, and the next pulse, the sand matrix. Heavy minerals were brought in with the sand phase and not with the gravels. Thereafter, as the energy-level dropped, transgression took place, with the deposition of finer-grained material, until a state of equilibrium was reached and deposition came to a standstill. End-of-cycle winnowing by the waters of the streams and the lake produced a greater concentration of residual heavy minerals on the erosion surface. Incipient tectonic activity caused tilting of the erosion surface, thereby producing the unconformable relationships between successive cycles. On the tilted surface, degradation was enhanced, winnowing intensified, and lag concentration brought to an optimum. Continued tectonic adjustment culminated in the prograding sedimentation of the next cycle. The turbulent gravels broke up the depositional floor and incorporated the thin streaks of lag gold and uranium of the unconformity. Thus, these minerals could have been introduced into the gravels in two processes – picking-up from the footwall sediments and downward infiltration during the sand pulse that succeeded the laying down of the pebbles.

Not having seen the Rand the writer should perhaps not make comparisons. However, the voluminous detailed descriptions of the rocks in the literature, provide a fairly reliable

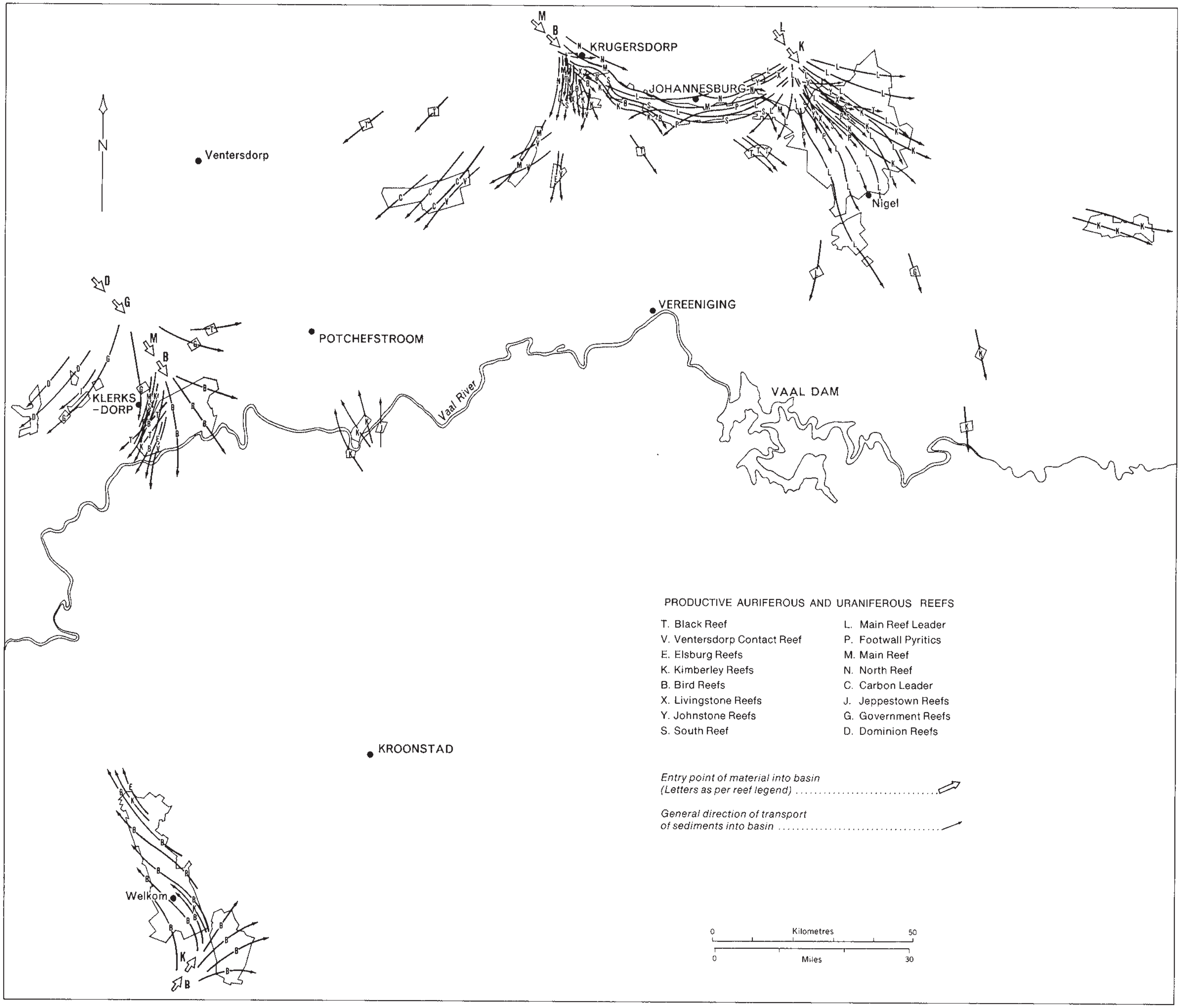
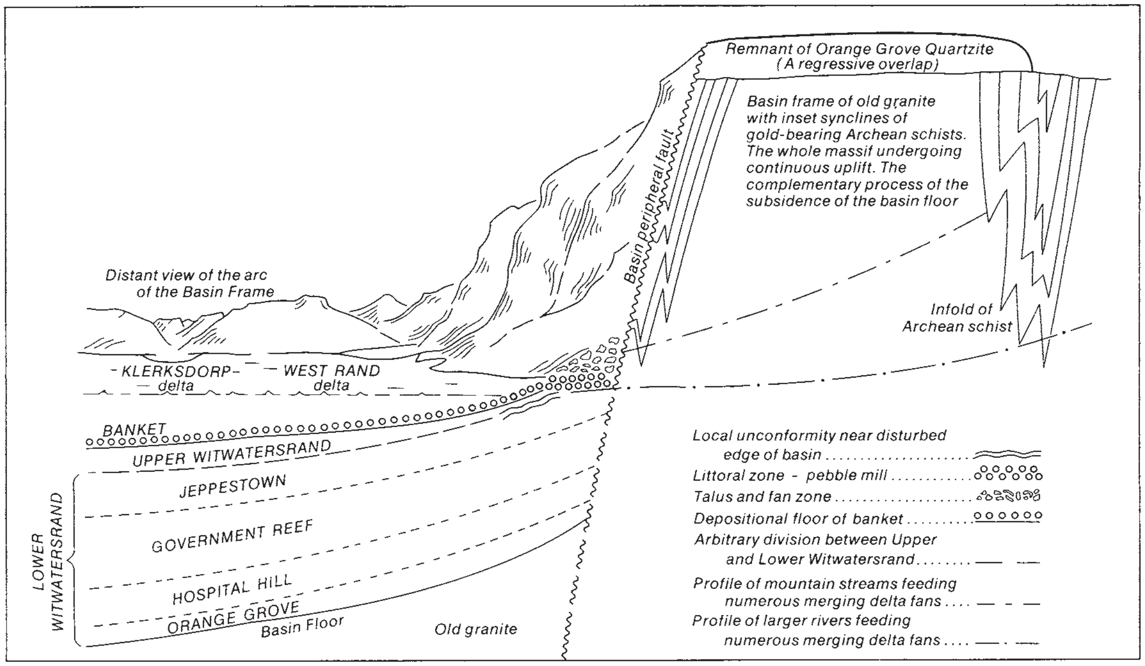
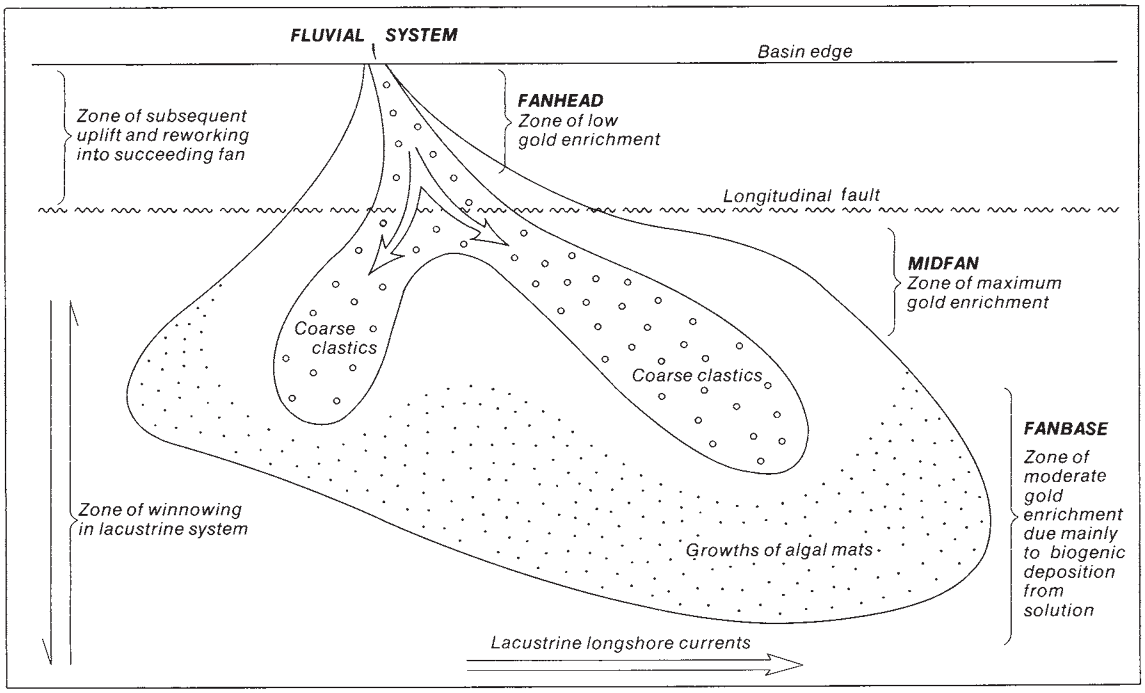


Figure 61. Sketch map of deltas and points of entry of sediment into the Witwatersrand Basin (after Brock and Pretorius, 1964*a,b*).



General concept-the banket, on a smooth depositional floor, is fed by ellipsoidal pebbles accumulated on the littoral 'pebble mill' released under exceptional but not cataclysmic conditions. The pebbles were moved by wave-bottom effects assisted by gravity (after Brock and Pretorius, 1964).



Detailed conceptual model of a Witwatersrand goldfield as a fluvial fan developed at the mouth of a major river flowing from a source-area in the northwest and debouching into a shallow-water, intermontane, intracratonic lake over a peripheral hinge-line consituted by faults parallel to the depositional axis. The general geometry of the fan, the various fan facies of deposition, the locations of coarse clastics and algal mats, the arrangement of varying zones of enrichment in gold, the portion of the fan subjected to transgression and winnowing and the clockwise flow direction of the longshore currents in the lake are shown (after Pretorius, 1975).

Figure 62. Diagrammatic sketches of the 'Basin Edge' concept of the formation of the Rand.

substitute for actual observations and permit some general comparisons.

There are a number of sedimentary basins that are analogous to the Rand and resemble it in many ways with respect to sedimentation phenomena, volcanism and tectonism. Most of these are in grabens or in subsidence zones bounded by profound fault systems. Here, we may mention the Michigan Copper Basin (Keweenaw Peninsula), the Sudbury–Blind River Basin, and the Bay of Fundy Basin in the Maritime Provinces of Canada. All are characterized by conglomerates and successions of grits, sandstones and quartzites interbedded or overlain by lavas commonly basaltic and frequently amygdaloidal. The mineralization in all of these basins differs considerably. Some are cupriferous, others uraniferous and still others uraniferous and auriferous as in the Rand. There are also analogies between the Rand and the so-called continental 'red beds' with their interbedded green beds. These constitute great basins filled with conglomerates, grits and sandstones. Some are cupriferous, others argentiferous, still others uraniferous; none are now known that are auriferous. Why should these major differences in mineralization occur in rocks that seem to have accumulated under similar conditions? We do not know the answer. Perhaps the parent rocks from which the sediments were derived were the controlling factor, or perhaps the degree of metamorphism and hence the extent of the redistribution and concentration of the various elements in the sedimentary and volcanic pile is the responsible factor. The latter seems the more probable.

Summaries of the types of gold (and uranium) mineralization in the Rand Basin are given by Pretorius (1964, 1975), and Brock and Pretorius (1964*b*). They distinguish the following types of occurrences of gold and uranium: (1) in the matrices of the conglomerates, (2) in banded pyritic quartzites, (3) in quartzites along a plane of unconformity between successive cycles of sedimentation, (4) on shales along planes of unconformity, (5) in carbon seams and thin films on parting planes between unconformities, or disconformities, (6) in quartz veins, and (7) in dykes.

Of these, only the first five constitute exploitable orebodies; the other two types have contributed to the production of gold on rare occasions and to a very limited extent. Those occurrences in categories (3), (4) and (5), according to Pretorius (1964, 1975), were formed in the terminal stages of one cycle of sedimentation, and those in categories (1) and (2) in the initial stages of a succeeding cycle. Categories (1), (2), (5), (6) and (7) are of most interest and are described in some detail below. Categories (3) and (4) are discussed mainly under category (2).

Conglomerate beds: These constitute the main orebodies of the Rand and are commonly referred to as 'banket' or 'reef'. Here belong the oreshoots or 'pay streaks' in the Dominion Reef; the Government, Coronation and Promise reefs in the Lower Division of the Witwatersrand System; the Elsburg, Kimberley, Bird and Main reefs of the Upper Division of the Witwatersrand System; the Ventersdorp Contact Reef; and the Black Reef at the base of the Transvaal System.

The conglomerates are composed essentially of pebbles of vein quartz with a few pebbles of quartzite and chert, all set in a matrix composed mainly of quartz, muscovite, sericite, chlorite, chloritoid and pyrophyllite (Pl. 15). In the matrix there is a veritable host of minerals occurring in variable amounts from place to place. Detailed descriptions of these minerals and their manner of occurrence have been given by Young (1917), Liebenberg (1955), Ramdohr (1955), Saager and Mihálik (1967), Saager (1968), Feather and Koen (1975), Barrass (1975) and a number of others (Haughton, 1964*a*). The list of minerals in the matrix includes:

Pyrite
Marcasite
Arsenopyrite
Glaucodot
Leucopyrite
Loellingite
Pyrrhotite
Sphalerite
Galena
Chalcopyrite
Cubanite
Bornite
Chalcopyrrhotite
Chalcocite
Covellite
Neo-diginite
Bravoite
Molybdenite
Stibnite
Mackinawite
Niccolite
Millerite
Pentlandite
Cobaltite
Linnaeite
Gersdorffite
Skutterudite
Safflorite
Tennantite
Tetrahedrite
Stomeyerite
Proustite
Dyscrasite
Bismuth
Tellurium
Magnetite
Hematite
Ilmenite
Goethite
Rutile
Anatase
Brookite
Ilmeno-rutile
Cassiterite
Chromite
Leucoxene
Monazite
Apatite
Xenotime
Zircon
Sphene
Garnet
Corundum
Diamond
Dolomite
Calcite
Tourmaline
Uraninite
Uranothorite
Brannerite
Thucholite
Graphite and carbon
Native silver
Platinoid alloys and minerals
Gold
Gold telluride(?)

Of these minerals pyrite is the most abundant constituting from 2 to 20 per cent or more of the matrix. It has been studied by Ramdohr (1958*a,b*) and classified in great detail by Saager (1970) (*see* Table 42). He distinguishes two general types – allogenic and authigenic[25] – with rounded, idiomorphic to hypidiomorphic (euhedral to subhedral) and xenomorphic (anhedral) morphologies. The xenomorphic pyrite occurs in veinlets and fracture fillings and is attributed to redistribution during metamorphism. The rounded (buckshot) pyrite is said to be partly detrital and partly due to pyritization of black sands and to concretionary processes, both having taken place in situ. Nodules containing 'mineralized bacteria' are thought to be due to the activity of primitive life. The idiomorphic to hypidiomorphic pyrite is thought to have been formed in situ as a result of reconstitution processes operating mainly during metamorphism. The pyrite is, therefore, considered to be partly detrital (allogenic) and partly due to syngenetic and metamorphic reconstitution processes (authigenic).

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[25] These two terms, originally introduced by Young (1917), for the minerals of the Rand are particularly appropriate. Allogenic minerals are those that have a detrital origin; authigenic minerals include all those that grew within the conglomerates. However, it is difficult to make a clear-cut differentiation between these two suites as anyone who has studied these ores will recognize. The classification depends on subjective interpretations made by eye or microscope using criteria that not all investigators agree are specific. How the authigenic minerals grew and the source of their constituents (syngenetic or introduced from distant sources) is also a matter of interpretation and has led to an enormous amount of controversy.

Hoefs *et al.* (1968) have investigated the sulphur isotopic composition of the allogenic (detrital) and authigenic (recrystallized or reconstituted) pyrite. Both types were slightly heavier than meteoric sulphur by only a few parts per thousand and are similar to what is thought to be magmatic sulphur (equivalent to the sulphur in the Palabora deposit). Since the samples showed no major shift in enrichment of ^{32}S the authors concluded that there was little biologic activity involved in the formation of the authigenic pyrite. On the contrary, they thought that the primary source of the pyrite was of magmatic rather than sedimentary origin. Their data, however, do show a slight shift toward enrichment of the lighter isotope in the reconstituted pyrite compared with the detrital variety. To the writer this may mean a fractionation in terms of a preferential mobilization of the lighter sulphur isotope during the reconstitution process as the investigators have suggested; the shift may, however, also be due to the activity of primitive organisms operating on sulphur of early Precambrian age. Thus, only slight shifts in the sulphur in Archean sediments in the Yellowknife area where bacterial (?) activity has been active have been noted (Wanless *et al.,* 1960). It would seem from these data that early Archean organisms had only a limited capacity to fractionate the sulphur compounds compared with their evolutionary descendents.

Pyrrhotite, arsenopyrite, the various base metal sulphides and the various sulphosalts and other metallic minerals are generally considered by most investigators to be authigenic minerals. Most of these minerals are present in only small amounts, although some such as pyrrhotite, galena, sphalerite and some of the Ni-Co minerals occur in some reefs in moderate amounts, in places in a massive, intergrown manner. Pelletier (1940) noted that high gold values were frequently associated with pyrrhotite and considered the mineral to be an enriching factor in Rand ores. The detailed relationship of gold (and uranium) to the various other base metal sulphides, sulphosalts, etc., and particularly the correlation with their elemental components, such as Sb, As, Co, Ni, Cu, etc. is relatively unknown, a gap in the knowledge of these deposits that should receive attention from the viewpoint of genesis of the metals. Microscopically, Liebenberg (1955) found that much of the gold was later (younger) than the base metal sulphides. In most of the reefs the authigenic gold commonly replaces pyrrhotite, chalcopyrite, pentlandite, sphalerite, cobaltite, linnaeite, galena and arsenopyrite.

The so-called 'carbon' of the Rand conglomerates and other types of closely associated deposits is a hydrocarbon-uraninite mixture probably best referred to as thucholite or uraniferous carbon. It was observed by the early workers, has been studied in detail by Macadam (1931), Davidson and Bowie (1951) and Liebenberg (1955) and is referred to at some length by De Kock (1964), McKinney *et al.* (1964) and others in the book edited by Haughton (1964*a*). The mineraloid occurs in a granular, columnar and massive form and is jet black to dull black in colour. Occasional thin sheets, stringers and veinlets are also encountered in some reefs. The granular variety occurs in the matrix of most reefs as small (0.1–4 mm) black spheroidal or nodular forms with a warty outer appearance. The ovoid granules frequently extend beyond the ends of the conglomerate lenses and are the only indication of the position of conglomerate horizons. The granules are generally distributed throughout the reefs, but in places there is often a concentration along the parting planes between the hanging wall and footwall of the reefs; in some areas the concentrations of granules are localized along the parting planes on the footwalls of the reefs. The massive thucholite resembles vitrinite and the columnar variety occurs as vitreous fibres normal to the bedding. The thickness of the seams of columnar and massive thucholite is generally only a few millimetres, rarely more than 1 cm. Both varieties are commonly associated with one another, or they may occur alone. Both may occur in the conglomerates, although they are more commonly found along the bedding planes of conglomerate bands and along the basal contacts of reefs. In the latter situation it is extensively developed in the "Carbon Leader" reef of the West Wits Line (De Kock, 1964).

The replacement, displacement and other growth features of the thucholite indicate that it is an authigenic mineraloid. Associated minerals include uraninite, gold, platinoids and sulphides such as pyrrhotite, chalcopyrite, pentlandite, sphalerite, cobaltite, linnaeite, galena and arsenopyrite. Microscope examination of the thucholite indicates that the uraninite commonly occurs as a large number of tiny inclusions in the mineraloid. Gold occurs as veinlets, specks and small irregular patches within the body of the thucholite; bands of gold also surround the granules of thucholite, and thin films and veinlets cut across the columns or occur with phyllosilicates between the columns of the columnar variety of the mineraloid. The various sulphides noted above commonly occur in the interstitial spaces between granules of thucholite and also appear in veinlets and patches in cracks and cavities in the mineraloid. Inclusion of sulphides in thucholite are also observed in places.

The intimate association of gold and thucholite in the Rand has been known and commented on for nearly 50 years. In and near the mineraloid, visible and occasionally coarse gold can be frequently seen, a feature that is unusual in the Rand ores. Thucholite is also rich in other metals in the "Carbon Leader"; besides gold there is native silver, a variety of platinoid minerals (sperrylite, braggite, cooperite, platiniridium, platinum and osmiridium), chalcopyrite, a number of Ni-Co arsenides and sulphides, sphalerite and galena (De Kock, 1964).

The origin of the thucholite is unresolved. Davidson (1964–1965) considers the mineraloid a carburan polymerized radiogenically from the methane and other hydrocarbon gases so prevalent in the South African mines. De Kock (1964) thinks the thucholite is possibly the organic remains of a primitive form of algae, which existed in the waters of the basin in which the reefs were deposited. Actually, the methane may be similarly derived, although it may have come from a very deep source as the result of abiogenic processes. Schidlowski (1966) considered that the carbonaceous material (thucholite) in the Rand formed by radiolytic polymerization of originally mobile (preferably gaseous) hydrocarbons percolating through the conglomerates, the prerequisite for its formation being the presence of detrital uraninite within the heavy fraction of the individual reefs. The writer is of the opinion that nearly all of these solid hydrocarbons are polymerized residues of petroleumlike materials derived in some manner, as yet unknown, from the humification of algae, bacteria and other low-order forms of life. There is a strong suggestion that these petroleumlike substances are capable of transporting gold, uranium, thorium and various other metals, probably in a chelated form. As they set (polymerize) in a gellike mass, resulting in the ovoid and columnar form of many of these hydrocarbons, the gold, uranium and other components are split out, appearing as minute inclusions or along cracks in the hardened gel.

The origin of the thucholite has been variously related to biogenic sources. Schidlowski (1965) found cell-like structures in the Witwatersrand rocks and Prashnowsky and Schidlowski (1967) identified amino acids and monosaccharides in the carbonaceous substances (thucholite). Hoefs and Schidlowski (1967) concluded from carbon isotope data of the thucholite that its constituents were of biogenic origin. The sulphur isotopic data on the allogenic and authigenic pyrite presented by Hoefs *et al.* (1968), however, showed only a small enrichment in ^{32}S in the recrystallized authigenic pyrite, suggesting only slight, if any, activity of organisms operating on the sulphur cycle in the conglomerates.

In a recent contribution to the origin of the carbon of the Rand, Hallbauer and van Warmelo (1974) have examined both the columnar and 'fly speck' types of thucholite from the Carbon Leader Reef and other auriferous reefs by scanning electron microscope. In the columnar type internal structures morphologically resembling filamentous, branched and apparently septate cells of obvious biological origin partly encrusted with gold were identified. In addition silicified structures that were identified as primitive fungi were noted. From these observations they concluded that the organism was some kind of a fossilized symbiotic lichenlike plant with no modern equivalent that formed carpetlike colonies of up to several square metres in extent. These organisms were capable of extracting gold and uranium from the environment and depositing them inter- and intracellularly. The 'fly speck' carbon constitutes spherical nodules with irregular and pitted surfaces showing a remarkable morphological resemblance to living fungal *sclerotia* (reproductive hyphae). The amorphous coallike thucholite is envisaged by Hallbauer and van Warmelo (1974) as due to exogenous plant debris washed into its present position and there attacked by a fungal organism.

Carbonaceous substances other than thucholite are found in the reefs and other rocks of the Rand Basin but generally only in small amounts. Liebenberg (1955) mentions the presence of nonradioactive bituminous matter in the reefs and quartz veins. The Black Reef conglomerate in particular contains appreciable quantities of a nonradioactive carbonaceous substance that together with chlorite is responsible for the colour of the reef. The gold in the reef is not closely associated with this carbonaceous matter.

Uraninite[26] was first noted in the Rand ores by Cooper (1923); its occurrence has been studied in detail by Liebenberg (1955). As already stated the uraninite is commonly present in thucholite as minute scattered particles. In addition the mineral occurs in the matrix, commonly as small rounded masses, isolated from the thucholite. The majority of this uraninite is said by Liebenberg (1955) to be detrital, an interpretation that a number of investigators have disputed at length. The uraninite in thucholite is, likewise, thought to be detrital, replaced to varying degrees by the hydrocarbon. Some of the microscopic uraninite is secondary occurring as tiny veinlets and irregular patches in cracks and cavities in the matrix. Most of the uraninite is thorium poor ($\sim 2\%$ ThO_2); the rare-earth content is of a similar order. Gold is closely associated with uraninite in most occurrences.

Most of the gold of the Rand conglomerate is extremely finely divided averaging about 80μ (0.08 mm) in diameter. Some is visible to the eye especially where the metal is closely associated with or in veinlets and patches in thucholite. Much of the gold occurs as tiny ragged particles or clusters of particles in the fine-grained matrix of the banket where it is generally associated with quartz, sericite and chlorite. It also occupies tiny fissures and cavities in most allogenic and authigenic minerals and may occur enclosed in or as replacements of secondary sulphides, especially pyrrhotite, pyrite, sphalerite, galena, etc. The general paragenetic relationship between gold and these sulphides is the same as that commonly seen in veins, namely that the gold is generally the last mineral to crystallize. Only minor amounts of gold occur in small rounded grains, and there are no descriptions of nuggets, large or small, such as one might find in Tertiary and Quaternary placers. This is confirmed by the recent work of Hallbauer and Joughin (1972) who examined the distribution and size of gold particles in the reefs. They found that all gold particles after release by hydrofluoric acid treatment passed through a sieve with apertures of 2.4 mm. All of the gold particles from the Kimberley Reef passed through a sieve with apertures of 0.075 mm. On the other hand, less than half the gold from the Vaal and Ventersdorp Contact Reefs passed through the same sieve. The separated gold had various shapes, the two most prominent forms being platelike particles with irregular edges and crystalline particles consisting of elongated octahedrons. Some of the crystalline particles were more complicated in their shape with branchlike extensions. Hallbauer and Joughin (1972) state that such similarly shaped particles have been observed in placer deposits.

The average grade of Rand gold ore is 0.25 oz Au/ton, the fineness of the native gold averages about 925, and the general Au/Ag ratio in the conglomerate deposits is approximately 9. According to Myers (1971) the fineness of the gold in the Rand is exceptionally uniform from particle to particle. The Ag/Au ratios in the various reefs of the Rand and the relationship of gold and silver have been intensively studied by Hargraves (1963), Von Rahden (1965), Schidlowski (1968), Saager (1969) and Viljoen (1971).

Hargraves (1963) found that low grade samples have high silver contents and vice versa, and that the silver content of bullion from individual reefs varies as a function of the

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[26] There has been much argument, mainly academic, on the use of the terms uraninite and pitchblende in the quartz-pebble conglomerates and other types of uranium deposits. In fact, pitchblende is a cryptocrystalline variety of uraninite, but some investigators insist on distinguishing between the varieties on the basis of their origin, composition (U/Th ratio), or habit. Neither of these bases is really satisfactory, but the composition of the mineral may be significant in some contexts. Thus, it appears that in the Dominion Reef the uraninite carries relatively large amounts of thorium whereas in the other reefs the mineral (pitchblende) is relatively low in thorium. This fact would seem to be significant in the origin of the uraniferous mineral in the various reefs. Similarly in pegmatites the thorium content of uraninite is commonly high (about 25%) whereas in vein deposits the thorium content is generally low, features that must reflect significantly different processes in the origin of these deposits.

relative elevation of the reef, i.e., the bullion of the shallow reefs has a higher silver content than deeper reefs of comparable grade. Hargraves interpreted these compositional gradients as the result of chemical rather than physical (detrital) processes and stated that in terms of the modified placer hypothesis for the origin of the gold, the gradients imply considerable redistribution of silver relative to gold during the 'solution' stage.

Von Rahden (1965) thought that his data, which show wide variations in the apparent fineness (and hence in the Au/Ag ratios) of channel samples from the same elevations and stopes in the Ventersdorp Contact Reef and Main Reef, could be ascribed to the presence of silver minerals (mainly native silver) in the ore. The silver minerals, he felt, were due to the redistribution of silver relative to gold during the solution stage of the modified placer theory suggested to explain the Rand deposits. Von Rahden (1965) further concluded that his results did not tend to confirm Hargraves' (1963) hypothesis that the silver content of the reefs varied with elevation. He recommended electron microprobe studies of the ore to resolve the problem.

Addie (1964), commenting on Hargraves' (1963) paper, considered that the increase in the Au/Ag ratio in the Witwatersrand deposits with depth is due to exsolution of a silver-gold solid solution as the temperature changes. By this he apparently meant that since the silver is more mobile it migrates out of the system. He thought that the increasing Au/Ag ratio signalled an approach to a thermal centre and postulated a thermal source for the mineralization.

Schidlowski (1968) investigated the gold fraction of the Witwatersrand conglomerates from the Orange Free State goldfield and confirmed that the bulk of the native gold is concentrated within the bottom parts of the 'reefs', mostly near the footwall contacts. This, together with other criteria, suggested to him that the distribution of the metal was governed by sedimentary processes. On the other hand, the shape of the gold grains and the general fabric of the gold-enriched layers often lack conspicuous sedimentary characteristics, a fact that he related to subsequent metamorphism, which produced marked structural modifications and a limited textural rearrangement of the gold and its host-rock, thus obliterating to a certain degree the primary alluvial character of the metallization. Schidlowski postulated that the large-scale reconstitution of the gold fraction was effected either by a mechanical reshaping of the malleable and ductile gold particles or by an intermediate solution process followed by reprecipitation. These processes he thought took place more or less in situ, the original sedimentary distribution pattern not being profoundly affected, whereas the individual allogenic gold grains were transformed into authigenic ones or sometimes even into major gold aggregates. Schidlowski found by electron-probe microanalysis that the gold contains on the average between 9.9 and 12.4 per cent silver, which he considered also suggestive of an alluvial origin. Schidlowski concluded that an integration of all available data strongly supports a modified placer theory for the origin of the Witwatersrand gold.

Saager (1969) studied the Au/Ag ratios of individual gold particles and of ore samples obtained from the Basal Reef conglomerate horizon of the Upper Witwatersrand System in the Orange Free State Goldfield. He found that the values of individual gold grains were exceptionally constant at about 12.31, whereas the Au/Ag ratios of the ore samples had markedly lower values and showed a large variation. He thought that these values indicated that the detrital gold was homogenized during transportation and sedimentation and that part of the original silver content was redistributed. Saager further postulated that the first refining of detrital gold particles occurred in streams that eventually drained into the Witwatersrand basin. A redistribution of the silver relative to the gold took place in the littoral zone of the basin, where the conglomerates were reworked by wave action and erosion. Supergenic enrichment of gold might also have taken place close to the original shoreline. These processes he believed accounted for a decrease in the Au/Ag values of ore samples towards the northwest in the area investigated. Finally, the gold was homogenized during the metamorphic period of the Witwatersrand System, when pseudohydrothermal transport and redeposition of certain constituents took place. The main portion of the silver content of the original alloy, which was redistributed during the various processes outlined above, is now present as finely dispersed silver minerals. The hypothesis of an elevation control of the Au/Ag values, as suggested by Hargraves (1963), was found to be improbable.

Viljoen (1971) compared the composition of gold from the Witwatersrand with that from the Barberton Mountain Land. The elements most frequently found in the gold of both types of deposits are silver and copper with occasional nickel. The silver content of the Witwatersrand gold was found to vary considerably (0.3–32.1%) compared with the smaller variation (3.6–21.6%) of the Barberton ores.

Summarizing, we can say that nearly all investigators agree that the gold in the Rand conglomerates is authigenic. Some postulate hydrothermal processes as its source and others a placer origin with later redistribution of the metal as a result of metamorphic processes.

The ore shoots, pay shoots or pay streaks in the conglomerate beds are thin bodies with extensive dimensions on both their strike and dip. Most shoots are only a few feet thick, and some are only inches or fractions of inches such as the Carbon Leader. In places a conglomerate band may thin to a single line of pebbles; in others the reef is manifest only by a parting plane along which gold, hydrocarbon and uraninite occur. On their dip and strike dimensions the shoots may be hundreds to several thousand feet long. There appear to be some differences as to the exact location of the pay streaks in the conglomerate beds. As noted above some investigators find that the bulk of the gold is concentrated in the bottom parts of the reefs in some areas. In other areas evidently this is not always the case since there are numerous statements in the literature that the gold shows no preference for the bottoms of the conglomerate bands, being distributed randomly throughout the reefs or in some cases even concentrated at the top of the conglomerate beds (Pretorius, 1964, p. 97). The longer axes of the streaks tend to be parallel to the longer axes of the pebbles in a number of areas and trend roughly in the same direction. Some streaks are braided. Reinecke (1927), who carried out an extensive study on the outline of the assay and stope plans in the Main Reef of the East Rand, found that the gold distribution radiated southeastward from a northwest source and coincided with well-graded pebbles, large pebbles, aligned pebbles and relatively wide sections of the reefs. He interpreted these features to indicate deposition of gold in stream channels and concluded that the gold was originally of placer origin. Brock and Pretorius (1964*a,b*) reiterate these general views:

> In any given goldfield the total amount of gold present per unit volume of strata in the Upper Witwatersrand Division is greater near the basin's edge than it is farther away. As the sediments fan out towards the centre of the basin so the amount of gold becomes progressively less. The number of conglomerate bands and the overall coarseness of the sediments also vary proportionately with the mineralization, indicating that the pebbles, the gold and the uranium were introduced into the basin contemporaneously and at the same point by the same transporting agencies.
>
> Paystreaks, representing better developed conglomerates and higher values, radiate outwards from the same points of entry. The East Rand affords the best documented example, but almost identical conditions exist in the Central Rand, West Rand, West Wits Line and Orange Free State. Although conglomerates are also present between the paystreaks, here the pebbles are usually not closely packed and have not been "milled" to the same degree of homogeneity, and the conglomerates carry uneconomic amounts of gold. It has been observed that the coarseness of the banket type reef, up to certain size limits, generally varies directly with the gold content. The higher velocities of the transporting media in the pay channels brought more and larger pebbles and more gold and uranium.
>
> With the development of empirical rules regarding the amount of gold with relation to the edge of the basin, all the readily available data pertaining to sedimentational trends of pay reefs were collected and reviewed. These include paystreaks, footwall channels, increase in pebble size, increase in number of pay reefs, and increase in total gold per unit area of cross-section. In each of four goldfields a shoreward convergence was demonstrated. The gold-bearing zones are essentially fan-shaped with a well-defined apex in each case. They can hardly be called anything but deltas.
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> The four apices, representing four points of entry (northwest of Krugersdorp; north of Benoni; northwest of Klerksdorp; and south of Welkom) (*see* Figure 61 in this bulletin), must represent points on the ultimate rim of the basin at that particular time. Thus we have confirmation regarding the essential correctness of our outlining of the basin and its basin edge ramifications, and confirmation too that the loss by erosion was not excessive.

The general scheme of formation of the Rand banket suggested by Brock and Pretorius (1964*a,b*) and Pretorius (1975) combines the earlier work of a number of investigators; it has been termed the basin edge concept and is shown diagramatically in Figure 62 and described in previous pages.

Banded pyritic quartzites. The banded pyritic quartzites occur in erosion channels, scoured in the shales, quartzites and conglomerates, beneath major auriferous horizons in the Main Reef Group, the Bird Reef and the Kimberly Reef Group of the Upper Witwatersrand Division and in the Black Reef Series of the Transvaal System. The thickness of these quartzites varies from thin streaks to many feet, and the channels containing the banded quartzites are up to 100 ft deep. The economic mineralized beds consist of dense, dark quartzites alternating with layers of pyrite and barren quartzite. The layers of pyrite follow the bedding in the quartzites. The mineralization of the pyritic quartzites is essentially the same as that described above for the conglomerates and need not be repeated. According to Pretorius (1964) thucholite and uraninite are present in the pyritic quartzite but are not necessarily associated with the gold. There is, however, a more definite relationship in the quartzites than in the conglomerates between a high pyrite content and sympathetic gold content. The quartzites normally contain only small ore shoots of gold and uranium, but some are relatively rich with average grades higher than those in the conglomerates.

In some parts of the Witwatersrand gold is concentrated on quartzites and shales along planes of unconformity. In these cases the thickness of the pay zone may be only fractions of an inch. The gold is usually very finely divided but may be visible in some specimens. According to Pretorius (1964) and others this gold is essentially detrital, formed in the terminal stages of one cycle of sedimentation.

Carbon seams and thin films. The best example of this type of orebody is the Carbon Leader described in detail by Swiegers (1940) and De Kock (1964). This horizon is generally a carbon-rich streak or seam in quartzites, grits or conglomerates, or a mixture of these. It commonly forms a thin footwall seam and is heavily mineralized with pyrrhotite and pyrite. On the seam rests a variable layer of pebbles of vein quartz and some angular chert fragments. The pebble band itself is only 2 to 3 in. thick and the carbon seam varies from a mere streak to a solid band of carbon up to 3 in. thick. The minerals composing the Carbon Leader include hydrocarbon (thucholite), gold, native silver, uraninite, various platinoids, pyrite, pyrrhotite, chalcopyrite, a variety of Ni-Co arsenides and sulphides (mainly skutterudite, gersdorffite, niccolite, millerite, pentlandite and cobaltite), sphalerite, galena, chromite, muscovite, sericite, pyrophyllite, chlorite, chloritoid, biotite, and minor amounts of cassiterite, rutile, leucoxene, brannerite, tourmaline and zircon.

The gold in the Carbon Leader horizon occurs as veinlets, specks and anhedral grains, and is predominantly associated with the phyllosilicates, which occur as infilling between the cracks and cavities of the columnar type of thucholite. The remainder of the gold is directly included in the hydrocarbon or occurs in association with the pyrite and quartz. The very wide fluctuation in the Au/Ag ratios in assays of the Carbon Leader is due to the presence of native silver.

The platinoid content of the Carbon Leader is high, up to 0.75 oz/1000 tons of ore milled (0.00075 oz/ton or 0.025 ppm) the various platinoids present include the arsenide, sperrylite; the sulphides braggite and cooperite; and the metallic minerals platiniridium, platinum and osmiridium.

Quartz veins. Gold-bearing quartz veins are relatively common in some parts of the Rand Basin. They appear to be more prevalent in the shales of the Lower Division of the Witwatersrand System than in the quartzites and other rocks of the Upper Division (Pretorius, 1964). Their presence is usually minimized by the placerists and emphasized by the hydrothermalists of whom Graton (1930) gives the most extensive description of these bodies.

The quartz bodies occur as definite veins and veinlets cutting the reefs and associated rocks, as flat seams and veins along parting and bedding planes, as large veins and irregular masses or 'blows' near dykes and faults and as irregular patches or blotches in the reefs. The mineralization of the quartz bodies comprises native gold, which may be coarse in places, massive pyrite or pyrrhotite, chalcopyrite and more rarely galena, sphalerite and arsenopyrite. Some of the quartz veins have been mined in the past, but in general most of these deposits are small and uneconomic.

Several investigators have noted that the ore-bearing conglomerates near the auriferous quartz veins are depleted in gold, indicating that the conglomerates have been impoverished to supply the gold in the veins. Furthermore, it has been noted that these quartz veins become consistently less auriferous and ultimately barren with increasing distance from the gold-bearing conglomerates and quartzites. These features suggest that the quartz veins are of late secretion origin, unrelated to the initial formation of the gold in the bankets.

Dykes. Low grade gold mineralization is present in certain dykes, particularly where these intrusives cut across the reef horizons (Pretorius, 1964). As an example Reinecke (1927) mentioned that the "South Rand Dike", in Crown Mines averaged 0.06 oz Au/ton over a length of 380 ft. The highest values recorded reached 0.225 oz Au/ton.

The interpretation of the origin of gold in dykes crossing gold horizons is frequently difficult. In some places gold increases as the dyke is approached; in others the reverse is true – the gold appears to have been swept out of the rocks adjacent to the dyke. Such phenomena are repeatedly reported in gold deposits. With respect to the Rand two examples need only be cited – one by Sharpe (1955) where gold is highly concentrated adjacent to the Van Ryn Deep dyke where it crosses the Main Reef Leader and the other by De Kock (1964) where the gold in the Carbon Leader was depleted where crossed by a basic dyke. The writer has observed similar phenomena where dykes cross gold deposits and has also observed that some diabase dykes become slightly enriched in gold where they intersect gold-bearing ore shoots. These differences in the migration habits of gold are difficult to explain in generalities. Each occurrence has to be studied in detail. In some cases fluids are released in the rocks adjacent to the dyke, which assist in the migration of the gold in the pre-existing deposits away from the hot source; in other cases thermal diffusion and dilitancy (fracturing, etc.) are involved and the gold moves toward and into the dyke especially during the late cooling stages.

Origin of the Rand gold deposits. No type of gold deposit has prompted as much discussion and argument with respect to the origin of its gold (and uranium) as the Rand. Four general theories have been advanced:

Early workers considered the gold to be strictly of placer origin without modification. A somewhat similar theory says the ores are syngenetic, but the result of chemical precipitation of gold rather than mechanical deposition of the metal (Penning, 1888; De Launay, 1913; Garlick, 1953). Miholić (1954) considered that the gold was a diagenetic addition to chemically precipitated uranium-hydrocarbon deposits, all later modified during metamorphism. He envisaged initial marine gravel deposits along a steep coast in which a rich vegetation of uranium concentrating organisms developed under anaerobic conditions giving rise to the formation of thucholite and pyrite. At a later period gold in an ionic form was reduced and precipitated by the organic matter from percolating thermal waters that invaded the conglomerates.

In a recent paper Reimer (1975) has postulated yet another variation on the syngenetic chemical theory for the origin of the gold and uranium in the Rand. Having analyzed the published age data from the western part of the Transvaal he concluded that the auriferous sediments of the Witwatersrand System were deposited over a period of about 30 to 40 m.y. during the time range of 2480 to 2370 m.y. The age relationship between these sediments and the over- and underlying formations he thought invalidated the concept of a "Witwatersrand Triad", which has been visualized as comprising the Dominion Reef, Witwatersrand and Ventersdorp systems, covering a time span of about 600 m.y. Reimer further opined that the age of the Witwatersrand System as deduced from his study has important implications for the origin of the gold in the conglomerates. Thus, doubt is cast on the simple model of its derivation as clastic grains direct from Archean greenstone belts. On the contrary it would appear that most of the gold was dissolved in trace amounts from rocks in the source area and transported in solution to the depository. Here it was precipitated, possibly aided by primitive organisms and then concentrated by normal sedimentary processes. Reimer also rejects derivation of the uraninite from pegmatitic sources and suggests that most of the uranium was transported to the depository in a dissolved form. It was then precipitated under strong organic influences to form nodular grains that, like the gold, were concentrated by normal sedimentary processes in the conglomerate horizons.

The most recent contribution to the origin of the uranium mineralization of the Witwatersrand and Dominion Reef systems is that by Simpson and Bowles (1977), who assume the presence of a depositional basin overlying an Archean craton enriched in oxyphile metals including uranium. In the basin they consider that uranium was deposited in two ways, as detrital allogenic uraninite and by precipitation from solution. The detrital components were concentrated in the higher energy conglomerate environment of the Dominion Reef and proximal parts of the Witwatersrand Basin. The solution components including uranium and gold were precipitated under reducing conditions through the agency of decaying organic matter in the lower energy or distal regions of the basin, giving rise through diagenesis and metamorphism to such uraniferous horizons as the Carbon Leader of the West Wits, which are not directly related to known paleogeographical channels. They further state that it can now be clearly demonstrated that relatively small amounts of thorium increase the resistance to attrition and oxidation to the extent that a thorian uraninite with 1 per cent or more thorium oxide can survive as river detritus under present-day atmospheric conditions. They find that all of the uraninite grains from the Witwatersrand Basin considered to be of detrital origin contain 1 per cent thorium oxide or more; hence, it is unnecessary to postulate a reducing atmosphere, indeed the retention of sulphate and uranyl ions in solution would seem to require the existence of an oxidizing atmosphere in the model proposed for the deposition of uranium from solution.

Most South African geologists writing on the Rand adhere to the modified placer theory. They argue that the gold was deposited as placer grains, the metal being later mobilized and recrystallized during the metamorphism of the rocks. Uraninite has suffered a similar fate. Advocates of this theory include Mellor (1916, 1931), Reinecke (1927, 1930), Young (1931), Macadam (1936), De Kock (1940), Du Toit (1940), Frankel (1940), Liebenberg (1955), Ramdohr (1958*a,b*), Bain (1960), Nel (1960), Brock and Pretorius (1964*a*), Schidlowski

(1968), Saager (1969), Viljoen *et al.* (1970), Minter (1970), Myers (1971) and Pretorius (1974*a,b,* 1975).

The third theory argues that the ores are of hydrothermal origin, although some investigators are hazy about the source of the gold. Presumably they consider that it derived from a cooling magma. The supporters of this theory include Hatch and Corstorphine (1909), Horwood (1917), Graton (1930) and Davidson (1953, 1957). The publication of Graton's treatise brought a veritable blizzard of criticism from the placerists most of which is published as an annex to the Transactions of the Geological Society of South Africa v. XXXIV, 1931, p. 1–92.

The fourth theory suggested by Davidson (1964–1965) states that the gold and uranium were leached from overlying volcanics by heated saline waters. These waters sank to the lowest permeable horizons mainly along the conglomerates and unconformities where they deposited their metals toward the cooler outer margins of the basins. This idea brought forth another storm of criticism, much of which was unfavourable to the mechanism (Bowie, 1964–1965; Collender, 1964, 1965; Dowie, 1964–1965; Rice, 1964–1965; Taylor, 1964–1965; Bishopp, 1964–1965; Gillett, 1964–1965; Way, 1965; Greenberg, 1964–1965). It was pointed out that the volcanics were generally impermeable and showed no evidence of leaching. There is also no evidence of saline beds ever having been present, none are present now, and there is no evidence of collapse structures indicating their former presence.

A considerable number of features are invoked to support the modified placer theory among which the following are the most important.

1. The great persistence of the mineralization in individual beds of conglomerate or sequences of beds.
2. A ready source of placer gold in the Swaziland System known to contain numerous gold-quartz deposits.
3. The presence of abundant quartz pebbles that is a feature of many placers including the Klondyke (White Channel gravels) and the Victoria placers in Australia (White Leads).
4. The presence of undoubted detrital minerals that commonly accompany gold in placers an example being the platinoid metal compounds, chromite, garnet, etc. Uraninite is, likewise, said by some investigators to be detrital, but this has been disputed.

Viljoen *et al.* (1970) and Saager (1973, 1975) have postulated a granite-greenstone provenance model for the gold and a number of other minerals in the Rand. They claim that all the available evidence suggests that the sediments of the two basins (Dominion Reef, Witwatersrand System) were largely derived from the erosion of a granite-greenstone terrane similar to the Barberton region of the eastern Transvaal. They showed that a correlation exists between the expected placer minerals derived from successive erosional levels of such a terrane, and the actual placer minerals encountered in the Dominion Reef and Witwatersrand systems. More recently Köppel and Saager (1973, 1974) have advanced lead isotopic data of sulphides (galena, tetrahedrite) in the auriferous deposits of the greenstones of the Swaziland Sequence, which compares well with that of some of the data from the sulphides (pyrite, galena) of the Rand deposits. From this they concluded that the greenstone belts of the Swaziland System and their numerous gold deposits contributed detritus to the Witwatersrand depository.

Modification involving redistribution, migration and recrystallization of gold is admitted by the placerists, who attribute these phenomena to metamorphism evidenced by the presence of abundant sericite, chlorite and secondary quartz.

The principal evidence advanced in favour of the hydrothermal theory is:

1. The gold as it is now found is not in the form of nuggets or dust; on the contrary it is similar in its various forms and aspects to epigenetic gold. The silver content is also high, a feature that is not generally found in placer deposits.
2. Much of the gold is not at the base of the conglomerate beds as is normal in placers; rather the gold is commonly scattered throughout the bankets; some is even at the top of the bankets.
3. The gold is in shoots or pay streaks that are not identifiable with true pay streaks, leads, bars, channels, etc. in modern placers.
4. The bulk of the pyrite is certainly not detrital; some pyrite is like that found in epigenetic deposits.
5. The bulk of the uraninite is probably not detrital; it is in veins and veinlets and scattered at random through thucholite.
6. The general paucity of detrital minerals, especially magnetite. The placerists claim, however, that the magnetite has been sulphidized.
7. The presence of elements such as Cu, Pb, Zn, Ag, etc. bound in various sulphides and sulphosalts. These minerals, all investigators agree, exhibit epigenetic features.
8. The presence of sericite, chlorite, carbonate, tourmaline and other hydrothermal minerals in the deposits. In places these show an intimate relationship to gold and seem to have been precipitated with it.
9. The presence of quartz veins in faults, fractures and gash fractures. These veins carry gold and a variety of epigenetic sulphides.
10. Similarity in some respects to copper deposits in conglomerates such as those in Michigan. The copper is obviously introduced into the conglomerates; why not the gold? The geological setting is somewhat similar as well. There are conglomerate and quartzites in a basin interbedded with volcanics and considerable evidence of igneous activity in both places (e.g., Duluth Batholith and Bushveld Complex).

When all of the factors are taken into consideration most of the South African geologists on the Rand favour a modified placer origin. But the story is probably not yet finished, for new information is forthcoming every year. As Saager (1968) has pointed out, the extremely complex and complicated ore paragenesis of the Rand can probably only be explained by a polygenetic origin of the different ore components, "With certain reservations, it is possible to obtain specimens from the Witwatersrand ores that exhibit classic hydrothermal, placer, or even syngenetic-sedimentary characteristics. 'Proof' can thus be obtained for any genetic interpretation it is wished to construe on the origin of the Witwatersrand conglomerate ores."

For one not familiar with the Rand it would seem that the overall geological and geochemical pattern is the key to the origin problem as it is in any other gold deposit. Specific criteria may be found that support the overall theory, but these may be overshadowed in some places by later effects that may be irrelevant but serve to confuse the pattern. After the description of the other conglomerate deposits in this category an attempt is made in the section on the origin of gold deposits to formulate a general theory on the origin of the conglomerate type.

The Tarkwa goldfield, Ghana

The Tarkwa goldfield in southwestern Ghana near the town of the same name is in a Precambrian terrane consisting mainly of a thick series of argillaceous and arenaceous sediments with two well-defined gold-bearing quartz-pebble conglomerate beds. These lie in a long narrow northeast striking syncline. The geology of the field has been described in detail by Hirst (1938) and Junner *et al.* (1942).

The geological column for the Tarkwa goldfield is given in Table 63, and a generalized geological section is shown in Figure 63. The oldest rocks, the Birrimian System, are essentially greenstone belts isolated by granites. They contain a number of gold deposits throughout their extent in Ghana. At Abuasi, some 70 mi northwest of Tarkwa, a number of gold quartz lodes occur in the Birrimian schists and phyllites. The Ashanti lode, the most productive, is a steeply dipping series of quartz veins in sericitic and graphitic schists and phyllites, containing essentially quartz, carbonates, sericite and small amounts of pyrite, arsenopyrite, sphalerite, galena and gold, the last mostly invisible to the eye. The average grade of the ore is about 1 oz Au/ton (Kitson, 1930). The Birrimian rocks and their deposits may have been the principal source of alluvial gold in the Banket Series of the Tarkwa according to a number of investigators.

The Banket Series consists of a conglomerate bed at its base known as the Basal or Main Reef, another series of conglomerates and breccia conglomerates termed the Middle Reef Series some 15 to 40 ft above the Basal Reef, and an upper Breccia Reef Series lying from 40 to 75 ft or more above the Middle Reef. In general the reefs strike northeast and dip from 30 to 50° toward the synclinal axis. The reefs tend to lense out along strike according to some investigations; others attribute this feature to strike faulting. A controversy has, therefore, arisen as to which is the more important (Hobson and Robinson, 1943; Junner and Hirst, 1944). The Basal or Main Reef carries the best gold values; in most places its oreshoots average about 0.27 oz Au/ton and the Au/Ag ratio ranges from 4 to 49. The Breccia Reef Series is low grade, averaging less than 0.05 oz Au/ton. The ore shoots in the Middle Reef tend to be short and low grade, averaging about 0.1 oz Au/ton.

The gold-bearing shoots of the Basal and Middle reefs are in beds or series of beds of quartz-pebble conglomerates (Pl. 16) interbedded with quartzites. The Breccia Reef consists of alternating bands of coarse to fine breccia and grit containing a large amount of Birrimian phyllite and schist debris in the form of squeezed pebbles, fragments and dust. Crossbedded seams of hematite occur throughout the series, particularly in the coarse members. The Basal and Middle Reef series consist of relatively persistent conglomerate beds interbedded with

Table 63. Generalized geological column, Tarkwa goldfield, Ghana

	System	Group, etc.	Lithology
Precambrian		Post Tarkwaian Intrusives	Epidiorite, norite, gabbro, amphibolite, porphyry, diabase and epidiorite
		Intrusive contact	
		Huni Sandstone	Sandstone, grit, quartzite and phyllite
	Tarkwaian	Tarkwa Phyllite	Phyllite and chloritoid phyllite with subsidiary arenaceous beds
		Banket Series	Quartzites, grits, breccias and banket conglomerates. Three reefs are recognized: a lower main or Basal Reef, a Middle Reef and an upper Breccia Reef
		Kawere Group	Sandstones, quartzites, grits, breccias and conglomerates
		Great unconformity	
	Birrimian	Upper Birrimian	Volcanics (greenstones), pyroclastics, phyllite, greywacke and manganiferous phyllite, intruded by and granitized in places to granites and porphyries. Also intruded by epidiorites in places

Source: Junner *et al.* (1942).

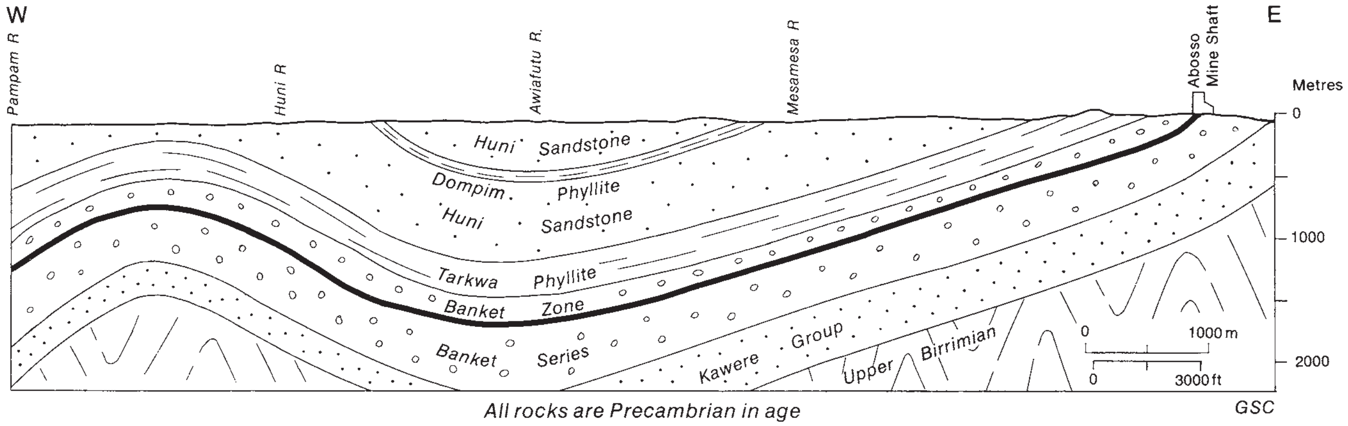

Figure 63. Generalized geological section across the Tarkwa goldfield, Ghana (after Hirst, 1938).

quartzites. The conglomerates are composed essentially of vein quartz pebbles and some quartzite and schist pebbles. The matrix of the conglomerate consists of quartz and black sand (mainly hematite admixed with ilmenite, magnetite and rutile) together with variable but minor amounts of sericite, chlorite, chloritoid, tourmaline, rutile, zircon, garnet and gold. Epidote, carbonate and pyrite are rare except near later dykes, faults and quartz veins. The black sand occurs as disseminated grains and aggregates of grains in the interstices between the pebbles of quartz and also in the form of bedded and crossbedded seams. Most investigators agree that the hematite and other constituents of the black sand are undoubtedly of detrital origin. The conglomerates and the associated quartzites are shallow water deposits deposited in a slowly sinking basin as witnessed by the presence of crossbedding, erosion channels and the occurrence of other features such as ripple marks in the Banket Series and in underlying and overlying sediments. Junner *et al.* (1942) state that the deposits are not lacustrine, glacial or aeolian deposits; they think they may have been either deltaic or fluvioglacial deposits.

The Banket Series and associated rocks have undergone regional metamorphism up to the chlorite-sericite stage. In addition a number of narrow quartz veins intersect the reefs, and small lenticular quartz veins are scattered throughout the Banket Series and other rocks of the Tarkwa System. In the mines the most common are those following footwall shears and veins with steep dips that traverse the reefs. The latter are commonly associated with dykes. Both types carry sulphides, mainly pyrite, chalcopyrite and galena. The gold values of the reefs are said to be unaffected by proximity to dykes or quartz veins.

The gold in the conglomerates is very fine grained and generally not visible to the naked eye. In general the gold values are highest and most persistent in well sorted and closely packed hematite-rich quartz conglomerates with a moderate thickness (1–6 ft). The gold is segregated into definite pay shoots separated by unprofitable intervals, and in the pay shoots the gold is segregated into definite zones. The wall-rock quartzites carry little or no gold, but some sporadic high assays are obtained where they contain an abundance of hematite. In several of the mines the gold is concentrated in the bottom foot of individual conglomerate beds. The bulk of the gold is intimately associated with the detrital hematite containing water-worn crystals of zircon and rutile. Individual particles of gold average about 60μ (0.06 mm) in diameter. This is approximately the size of the gold in alluvial placers in a number of Ghanian rivers according to Junner *et al.* (1942). The particles of gold as seen in polished and thin sections tend to be irregular and hackly, and they are commonly associated with a green talcose mineral. They are certainly not now in the form of placer nuggets or dust, a feature that indicates either remobilization of placer gold or deposition from hydrothermal solutions.

As with the Rand two general theories have been suggested to explain the occurrence of gold in the Tarkwa conglomerates, Junner *et al.* (1942) consider the gold to be of placer origin, later remobilized and recrystallized. Rozhkov (1967) agrees with this theory. Bray (1928), however, attributes the mineralization to ore-bearing solutions, but does not state from whence came the gold except to suggest a deep-seated source.

The arguments used in favour of each theory for the origin of the gold in the Tarkwa deposits are essentially the same as those for the Rand. Junner *et al.* (1942) have summarized the principal evidence for each theory as follows:

For the placer theory:

1. Gold occurs in varying amounts in the folded and metamorphosed Banket Series conglomerates throughout the Gold Coast. On the other hand it is rare in the underlying Kawere conglomerate, which is also of Tarkwaian age, and is also rare in quartz veins and igneous intrusions cutting the Tarkwaian.
2. Auriferous quartz veins and lodes are abundant in the Birrimian – the next oldest formation to the Tarkwaian – and there is abundant evidence that the Banket Series beds were largely derived from the Birrimian.
3. The gold in the veins and lodes in the Birrimian and also in the streams draining Birrimian rocks is of similar size to that in the banket conglomerates.
4. Although intrusive igneous rocks are abundant in the Tarkwaian in the Tarkwa goldfield and there is evidence of hydrothermal action accompanying them, the auriferous conglomerates are little altered. The detrital black sand in the banket and adjacent wall rocks has not been replaced by sulphides except in a very few places alongside intrusions and quartz veins, and carbonates and sulphides are absent or rare in these rocks. Elsewhere in the world carbonates and sulphides almost invariably accompany gold deposits of hydrothermal origin.
5. The distribution of the gold in the banket in the Tarkwa goldfield is clearly related to sedimentary features.
6. The fineness of the gold (950–1000) is consistently high and is appreciably greater than the average of the fineness of hydrothermal gold.

For the hydrothermal theory:

1. The gold is not water worn, nuggets are absent, and the gold is more finely divided than normal alluvial gold.
2. The occurrence of most of the visible gold and of some of the invisible gold appears to be controlled by minute fractures and shear planes, particularly along the footwall contacts of the conglomerates.
3. The presence of tourmaline, chlorite, sericite and secondary quartz, and rarely some carbonate and sulphides, in the conglomerates and in quartz veins and dykes cutting them.
4. Gold occurs only occasionally in the quartz pebbles.

A recent sedimentological study of the Tarkwaian gold deposits by Sestini (1970, 1973) suggested that rather than a plain with a very low gradient, the site of deposition was an east-sloping pediment surface formed by coalescing alluvial fans. Most of the gold was derived from primary quartz veins in the Birrimian, to the west of Tarkwa; a small contribution may have come from gold-quartz-tourmaline veins in the Birrimian east of Tarkwa.

Jacobina auriferous-uraniferous conglomerates, Brazil

The auriferous-uraniferous Jacobina conglomerates of Brazil occur about 170 mi northwest of Salvador, Bahia, Brazil. They are of Precambrian age and have been described in some detail by White (1956), Bateman (1958), Leo *et al.* (1964), Cox (1967), Lemos (1974), Robertson (1974) and Andrade Ramos

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and Fraenkel (1974). The generalized geological column for the Jacobina Series is shown in Table 64 and their distribution in Figure 64.

The Jacobina Series lies in a long narrow fault block lying within the predominant gneissic terrane of the Brazilian Shield. In general the sediments of the series strike north and dip steeply (55–80°). They are cut by a number of steep angle transverse faults, some with considerable throw. According to Cox (1967) the grade of metamorphism imposed on the sediments corresponds to the amphibolite facies of regional metamorphism.

The rocks of interest are the auriferous conglomerates, which occur as lenses and beds up to 1 m thick separated by thicker beds of quartzites. These lenses and beds exhibit scour and fill structures at their base, and crossbedding and more rarely ripple marks are prominent in the conglomerates and quartzites indicating shallow water conditions. The conglomerates are composed essentially of pebbles of vein quartz set in a matrix of quartz, sericite, fuchsite and chlorite, with small amounts of magnetite, tourmaline and zircon. Two types of conglomerates are recognized, Piritoso and Chabu. The former, as the name implies, is heavily mineralized with pyrite, the latter contains little pyrite, the quartz pebbles being cemented by an arenaceous matrix. The gold and uraninite are concentrated in the Piritoso type.

Gold has been won from a number of mines deriving ore from the Piritoso type of conglomerates. These include Serra Branca, north of Jacobina, and the Canavieiras, Morro do Vento and João Belo mines to the south (Fig. 64). The production from these mines is small, and only the Canavieiras is operating at present (1975), milling about 50 tons/day of ore. The grade is variable ranging from 0.25 to 0.45 oz Au/ton and the uranium (U_3O_8) content appears to range from 0.008 to 0.05 per cent. Thorium is present only in trace amounts.

Table 64. Generalized geological column, Jacobina Series, Serra de Jacobina, Brazil

	Formation	Thickness (m)	Lithology
			Ultramafic sills and dikes; amphibolite lenses and dykes in places
		Intrusive contact	
Middle Precambrian(?)	Cruz das Almas	2100(+)	Pelitic schists, micaceous quartzite and minor conglomerate
	Rio do Ouro	2000–2300	Well bedded white to pale green quartzites with locally prominent ripple marks and crossbedding
	Serro do Córrego	1800–2000	Interbedded quartzite and auriferous conglomerate
	Bananeira	1000(+)	Massive coarse-grained pelitic schist; interbedded quartz muscovite schist and micaceous quartzite
	Lower Precambrian of Brazilian Shield (?)	?	Gneisses and granitic rocks, skarn, etc.

Source: Leo *et al.* (1964) and Cox (1967).

The ore-bearing Piritoso type of conglomerate contains from 2 to 5 per cent pyrite in the matrix of the conglomerate. There are in addition native gold, uraninite (pitchblende), chalcopyrite, pyrrhotite, sphalerite, ilmenite, molybdenite, rutile, brannerite and zircon (Ramdohr, 1958*b*; Gross, 1968). Thucholite is not mentioned as being specifically present in the Jacobina deposits, but in other similar deposits in Brazil (Belo Horizonte) small rounded balls of the mineraloid carry inclusions of uraninite (Robertson, 1974). Chromian muscovite is widespread in the quartzites and conglomerates, especially near the zone of the Jacobina fault (Leo *et al.*, 1965). According to Leo *et al.* (1965), the mineral is not of magmatic origin. Instead, the probable sources of the chromium are detrital chromite in original quartz sandstone beds, and chromium leached from ultramafic rocks by hydrothermal solutions in the Jacobina fault zone and introduced into adjacent quartzite layers. The gold is extremely finely divided varying in size from 0.05 to 0.1 mm. It is concentrated in the Piritoso conglomerates in ore grade levels but has a widespread distribution in nearly all conglomerates being present in average amounts of 0.015 oz/ton (0.5 ppm) according to Gross (1968). In the pyritic reefs the gold is included in pyrite grains, and minor amounts occur as thin sheets in fracture zones that cut the conglomerate layers.

The distribution of the gold shoots is of interest. White (1961) noted that the pyrite-gold-uraninite zone in the Morro do Vento followed a fracture that cut across all lithologic units. Similar features are apparent at the Serra Branca Mine according to Cox (1967). Gross (1968) mentions that there is no particular relationship between primary sedimentary structures such as size of pebbles, texture of pebbles (glassy or sugary), degree of sorting or rounding, or matrix-to-pebble ratio. He further states that in a number of beds in the Canavieiras Mine the gold is concentrated in the tops of the conglomerate beds. He does not think that the intrusive ultramafic rocks, which invade the reef horizons in places, have had any marked effect on the distribution of the gold. There is also no evidence to suggest that the dykes introduced the gold. Cox (1967), however, suggested that gold migration and deposition seems in places to have been controlled in part by the dykes of ultramafic rocks.

The same theories for the origin of gold at Jacobina have been suggested as for those in the Rand and Tarkwa, namely the hydrothermal and modified placer theories. White (1961), noting that the mineralization is crosscutting as mentioned above, considered that the gold and uraninite were emplaced by hydrothermal solutions introduced along a north-south fracture or fracture zone, apparently parallel to the bedding. This conclusion, he felt, was strengthened by the presence of quartz stringers and veins and the extensive sericitization and chloritization. Cox (1967) concluded that a placer origin for the deposits is probable but that there has been considerable redistribution of the minerals during metamorphism. Gross (1968) also suggested a modified placer origin for the auriferous conglomerate of the Canavieiras Mine. He quoted the following evidence in support of the theory:

1. Gold is found in the matrix of practically all the conglomerates in the mine area.
2. Economic concentrations of gold occur in a foreset system of cross-beds.

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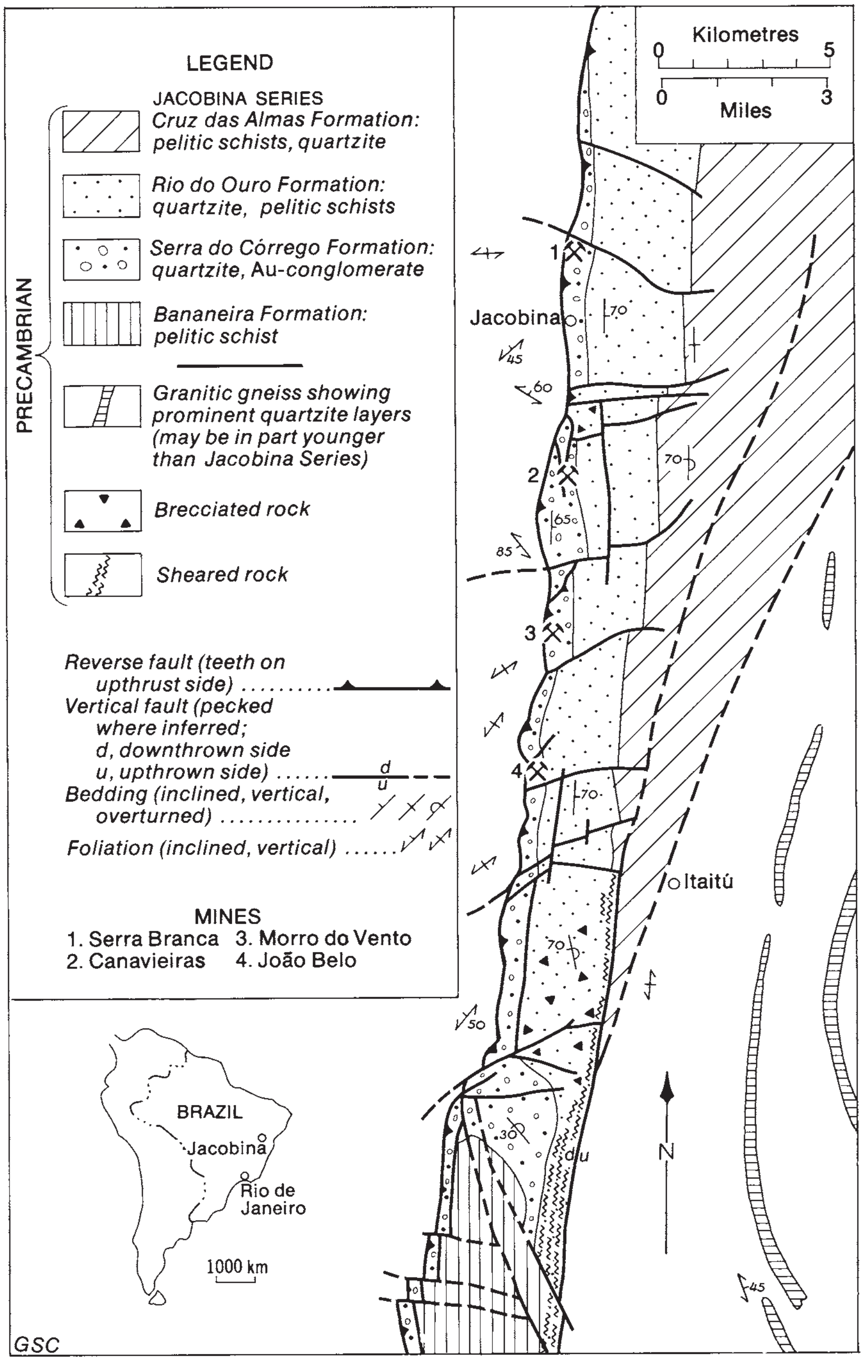

Figure 64. Generalized geological map of the southern part of the Serra de Jacobina, Brazil (after Cox, 1967).

Evidence suggesting that the placer gold was redistributed within the conglomerates during folding, metamorphism and intrusion is as follows:

1. Gold tends to concentrate towards the top of conglomerate beds.
2. Occasionally gold is found in tiny fractures that cut pebbles of the conglomerates.
3. Pitchblende occurs with high-grade gold ore.
4. Concentrations of gold occur near the contacts of ultramafic dyke intrusions.

Blind River–Elliot Lake uraniferous conglomerates

The Blind River–Elliot Lake conglomerates contain uranium, thorium and rare-earths (mainly yttrium earths). Gold values are erratic and of no consideration in the economic value of the ores. The deposits are briefly described solely for the purposes of comparison.

The Blind River–Elliot Lake area is north of Lake Huron some 95 mi west of Sudbury. The geology of the area and mineralization of the uraniferous belt has been described in detail by Collins (1925), Joubin and James (1957), Hart *et al.* (1957), Robertson and Steenland (1960), Lang *et al.* (1962), Pienaar (1963) and Roscoe (1969), all of whom also give extensive bibliographies.

The geological column for the Blind River-Elliot Lake district is shown in Table 65 and a generalized plan and section is shown in Figure 65. The rocks of interest are the Matinenda Formation at the base of the Proterozoic Huronian Supergroup. These contain all of the uraniferous orebodies.

Table 65. Generalized geological column, Blind River–Elliot Lake district, Ontario

			Group	Formation	Lithology
Precambrian	Proterozoic				Nipissing quartz diabase; granite; olivine diabase
			Intrusive contact		
		Huronian	Cobalt		Conglomerate, arkose, quartzite, greywacke and argillite
			Quirke Lake	Serpent	Subarkose, argillite and conglomerate
				Espanola	Limestone, siltstone, argillite, calcareous sandstone and conglomerate
				Bruce	Paraconglomerate, greywacke, subarkose
			Hough Lake	Mississagi	Subgreywacke, subarkose, siltstone, shale
				Pecors	Argillite, siltstone, greywacke and subarkose
				Ramsey Lake	Paraconglomerate, subarkose and greywacke
			Elliot Lake	McKim (300 ft)	Argillite, siltstone, greywacke and quartzite
				Matinenda (10–800 ft)	Quartzite, subarkose and uraniferous quartz pebble conglomerates Residual palaeosoil in places
			Great uncomformity		
	Archean		Basement complex		Volcanics (greenstones), cherty iron formation, granodiorite, pegmatites and other granitic rocks

Adapted from Table IV-4 *in* Douglas (1970).

The Matinenda Formation is composed essentially of oligomictic conglomerates interbedded with beds of quartzite and subarkose, all metamorphosed to the sericite facies. The conglomerates are composed mainly of well rounded vein quartz pebbles with a few pebbles of chert, feldspar and acidic volcanics in a matrix of quartz, feldspar and sericite. The conglomerate beds range in thickness from 1 in. to 10 ft. Crossbedding is common in the quartzites and conglomerate beds and scour channels are frequent. Locally the conglomerates and quartzites are intersected by irregular albitite dykes, and there is considerable albitization of the conglomerates in places, particularly at the Pronto Mine (Fig. 66). Many conglomerate beds are heavily mineralized with pyrite (av. 3–5%; max. 25%) and some carry economic quantities of uranium. There are in addition considerable concentrations of thorium and rare-earths (mainly yttrium earths). The average uranium content of the ores throughout the district is about 0.12 per cent U_3O_8, but some sections of conglomerates and quartzites are exceptionally rich containing percentages of U_3O_8 according to the writer's observations. These frequently occur where there is extensive crossbedding. The average thorium content appears to be about 0.05 per cent ThO_2 and the average rare-earth (mainly yttrium earths) content about 0.25 per cent. The gold content is exceptionally low averaging about 0.003 oz/ton (0.09 ppm) according to analyses done for the writer. The reserves of uranium and thorium ore in the Blind River–Elliot Lake district approach 300 000 000 tons averaging 0.1 per cent U_3O_8 and 0.05 per cent ThO_2. Enormous tonnages of grades at 0.01 to 0.05 per cent U_3O_8 and 0.005 per cent ThO_2 are available. The mineralogy of the ores has been extensively studied by Traill (1954), Nuffield (1954), Roscoe (1959), Roscoe and Steacy (1958) and Robertson and Steenland (1960). They list the following minerals as being present:

Pyrite
Pyrrhotite
Chalcopyrite
Galena
Sphalerite
Molybdenite
Marcasite
Cobaltite
Brannerite
Uraninite
Pitchblende
Monazite
Zircon
Uranothorite
Coffinite
Thucholite
Ilmenite
Hematite
Magnetite
Sphene
Anatase
Rutile
Chromite
Spinel
Epidote
Sericite
Biotite
Chamosite
Garnet
Greenalite
Grunerite
Tourmaline
Chlorite
Amphibole
Diopside
Apatite
Cassiterite
Fluorite
Barite
Carbonate

The most abundant metallic mineral is pyrite, which is disseminated in small grains and aggregates of grains in the matrix and around the borders of the quartz pebbles. The grains are anhedral to euhedral, and there is much spheroidal or 'buck-shot' pyrite. Some of the pyrite contains leucoxene cores suggestive of sulphidization of titaniferous magnetite. The principal uranium minerals are uraninite and brannerite. The brannerite tends to occur in the matrix in ovoid aggregates about 0.3 mm in diameter that also carry anatase or rutile. Uraninite is commonly present as anhedral to subhedral grains about 0.1 mm in diameter. It normally contains about 5 per cent ThO_2. In pyrite streaks in both conglomerates and quartzites there is usually considerable uraninite in aggregate form, and certain crossbedded parts of the beds may

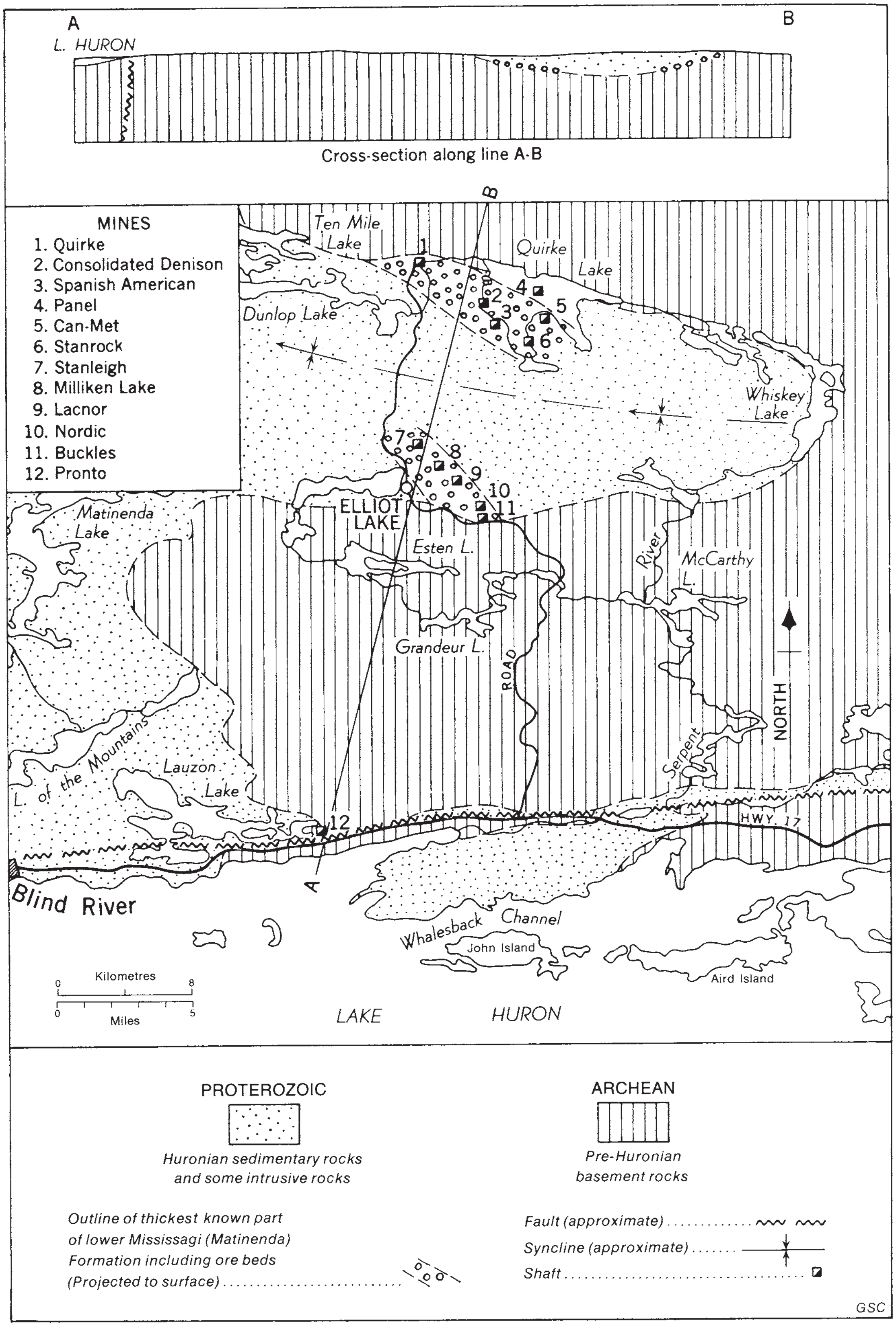

Figure 65. Diagrammatic geological plan and cross-section, Blind River–Elliot Lake area, Ontario (after Lang *et al.*, 1962).

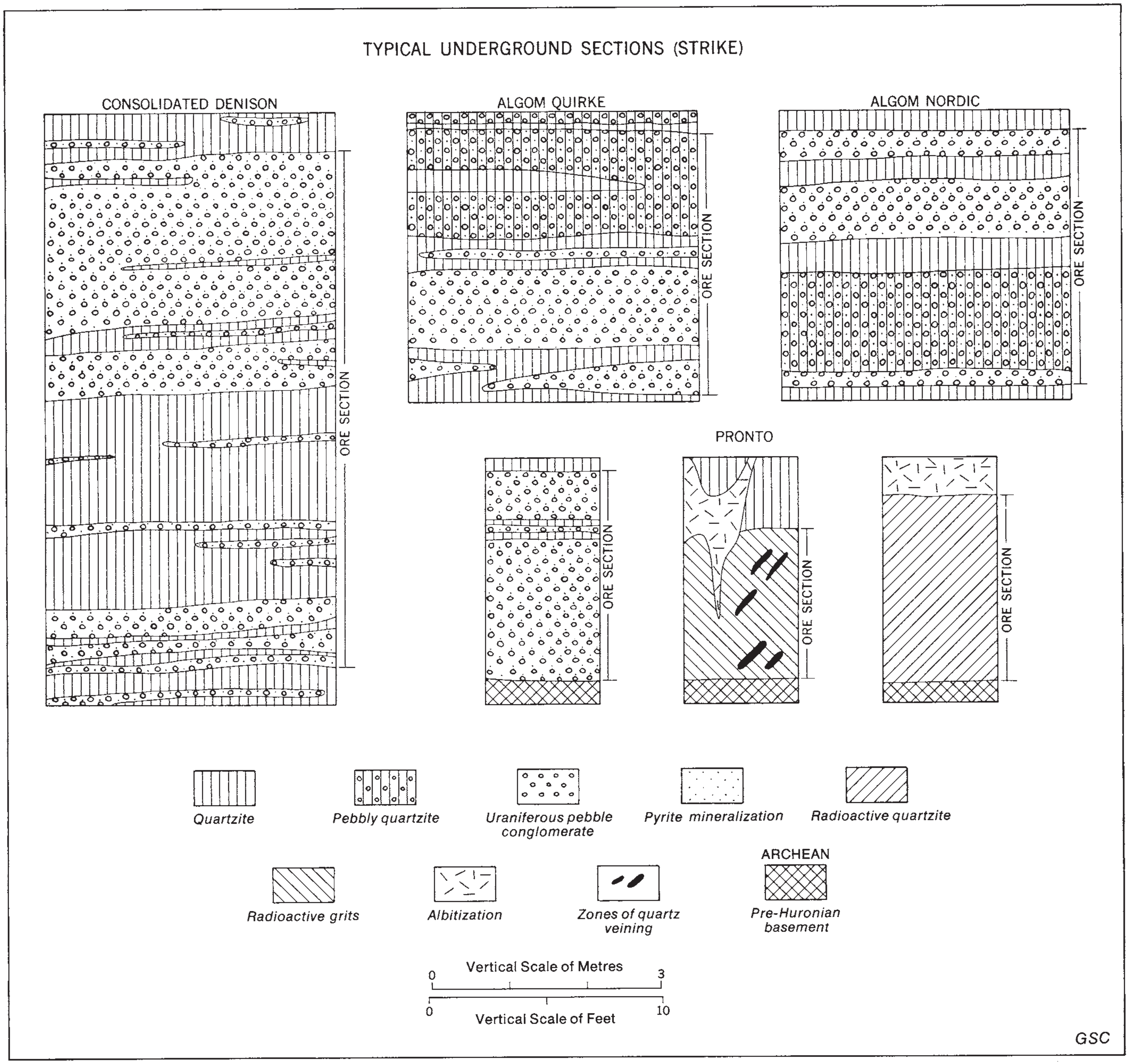

Figure 66. Typical underground sections of Lower Proterozoic uraniferous conglomerates, Blind River–Elliot Lake area, Ontario (after Lang *et al.*, 1962).

be made up of nearly massive aggregates of uraninite. There is commonly a higher content of uraninite in pyrite-rich parts of the beds. Thucholite was not seen in the matrix of the conglomerate or quartzite by the writer; it occurs, however, as warty aggregates along faults and fractures in places and as thin columnar seams with uraninite and pyrrhotite along bedding planes. Ruzicka and Steacy (1976) describe some of the latter occurrences in detail.

Gold and silver occur in the Blind River–Elliot Lake ores only in small amounts, the average gold content for most samples being 0.09 ppm (0.003 oz Au/ton). Locally, high assays can be obtained particularly where sulphides such as galena, sphalerite, cobaltite, etc. occur. Most of the gold and silver are in the pyrite and sulphide concentrates as indicated by assays of these materials in our laboratories. The average for the pyrite and mixed sulphide concentrates is about 0.64 ppm (0.019 oz Au/ton). No native gold was seen in these concentrates by the writer, but the metal has been reported as occurring sporadically in some of the ores.

The oreshoots in the Blind River–Elliot Lake mines are usually gently dipping tabular bodies composed of lenses and interfingering beds of pyritic quartz-pebble conglomerates and quartzites as shown in Figure 66. In most of the stopes the pyritic mineralization of both the conglomerates and quartzites commonly shows a wispy to banded appearance, and there is undoubted evidence of replacement of crossbedded features by pyrite and uraninite. One can also see seams of pyrite along bedding planes, veinlets of pyrite in the quartz pebbles in places and little trains or veinlets of uraninite (pitchblende) in the matrix of the conglomerates. All conglomerates and quartzites rich in uranium are generally always relatively rich in pyrite, but the converse is not necessarily true. Sericite-rich areas seem to be indicative of high uranium contents in most samples. Finally, in some areas quartz veining is evident. These and isolated fractures contain pyrite, chalcopyrite, pyrrhotite, galena, sphalerite and occasionally cobaltite. They are not radioactive.

On the question of origin the two general theories – hydrothermal and modified placer – common to these types of deposits prevail. The early workers (Joubin and James, 1957; Holmes, 1957) supported the modified placer theory and later workers have tended to agree (Roscoe and Steacy, 1958; Robertson and Steenland, 1960; Bain, 1960; Pienaar, 1963; Robertson, 1974). Davidson (1957, 1964–1965), however, maintains that the uraniferous ores are hydrothermal or due to downward leaching by saline waters as explained in the section on the Rand.

Other Precambrian occurrences of uraniferous and auriferous quartz-pebble conglomerates in Canada

Quartz-pebble conglomerates are developed in a number of other districts in the Canadian Shield; many contain uranium and thorium with minor amounts of gold, others are considerably enriched in gold as well as in uranium and thorium. East of the Blind River–Elliot Lake district, some 35 mi west of Sudbury, the basal Huronian rocks yield uranium from the Agnew Lake Mine. The pyritic oligomictic conglomerates comprising the ore horizons are steeply dipping and extend to depths of 3000 ft or more. The principal ore mineral is uranothorite, and the Th/U ratio in the ores is about 3:1 compared to 1:2 for the Elliot Lake deposits. Gold is found only in traces. Somewhat similar pyritic conglomerates and quartzites occur elsewhere along the base of the Huronian Supergroup west and east of Sudbury, one particular occurrence of note being present at the southwest corner of Lake Wanapitei. This conglomerate contains essentially monazite and leucoxene as the radioactive minerals; gold occurs only in traces.

Uraniferous occurrences in the Montgomery Lake–Padlei area of Northwest Territories are in Aphebian pyritic oligomictic conglomerates in the Montgomery Lake Group, which underlies the predominantly clastic Hurwitz Group and rests on rocks of Archean age. The occurrences contain abundant pyrite with uranothorite, zircon, leucoxene and notable amounts of gold (up to 0.1 oz Au/ton).

Occurrences of highly deformed pyritic uraniferous conglomerate, probably of Aphebian age, and belonging to the Sakami Formation, lie on Archean greenstones and greywackes on the west side of Sakami Lake in northern Quebec. Locally they carry in excess of 10 per cent pyrite and contain disseminated uraninite (with 10% ThO_2) and a thorium silicate, either thorite or allanite (Robertson, 1974). Gold occurs only in traces as far as is now known. Other basal quartz-pebble conglomerate lenses occur in quartzites and arkoses in the Papaskwasati Basin north of Lake Mistassini in Quebec. These belong to the Papaskwasati Formation of the Mistassini Group of Aphebian age, contain minor pyrite, are radioactive and have received some attention. Their gold content as far as is now known is low.

> The large nuggets found in the drift are simply the reliquiae of the chief masses of gold which once occupied the uppermost parts of the reefs, and that like the blocks of many an ancient conglomerate, they have been swept from the hilltops into adjacent valleys by former great rushes of water.
>
> –Murchison, Siluria, 5th ed., 1872

Placer deposits

Placer deposits provided early man with the first samples of gold and since that time have accounted for a large production of the metal. If we include the Witwatersrand and other quartz-pebble conglomerates as fossil placers or modified fossil placers, then the placer type of deposit has provided more than two-thirds of man's store of gold.

Before proceeding further certain terms with respect to placers should be defined.

The term 'placer' is evidently of Spanish derivation and was used by the early Spanish miners in both North and South America as a name for gold deposits found in the sands and gravels of streams. Originally, it seems to have meant 'sand bank' or 'a place in a stream where gold was deposited'. While many other terms have been coined for deposits in weathered residuum and alluvium none is quite as succinct and expressive as 'placer'.

The terminology of the zone or stratum containing an economic concentration of gold in eluvial and alluvial placers is varied. We shall use the miner's term 'pay streak', which is commonly used in Canada and the United States. Other

English terms in use include 'pay gravel', 'pay sand', 'pay dirt', 'pay wash', 'pay channel', 'pay lead', 'run of gold', 'gutter' and 'wash dirt'. There are a host of Spanish terms used mainly in Mexico and South America, and there are also miner's terms for the rich gold zones in practically all languages where eluvial and alluvial placers are worked. Rickard, many years ago, advocated the use of "gold-bearing channel" for all these terms, but it has not been generally accepted.

The tenor of pay streaks or of placer gold gravels and sands, in general, is referred to by the value (in ounces, pennyweights, or in any unit of currency) per cubic yard, per running foot of channel or per square foot of surface; also occasionally in bonanzas by dollars or some other unit of currency per pan. It is of interest to note that placer deposits can be worked whose gold content is as low as 0.1 ppm.

The pay streaks of placer deposits may rest on or near bedrock or on some stratum above bedrock. The bedrock in placer deposits is commonly referred to as the 'true bottom', although the term is little used today. When the streaks rest on a well-defined stratum of sand, gravel, shingle or clay above the bedrock they are said to be on a 'false bottom'.

Placers have been variously categorized, but here we shall use a simple nomenclature based upon whether the placers are formed by concentration of gold in situ over or in the immediate vicinity of primary deposits, namely 'residual' or 'eluvial placers', or by agencies that have concentrated the gold in the near vicinity or at some distance from the primary source. In the latter category we recognize 'alluvial', 'beach' and 'aeolian placers'. The terms 'saprolite' or 'saprolitic placer' were formerly used for certain types of eluvial placers, mainly in the eastern United States.

Eluvial, alluvial, beach and aeolian placers may become buried after their formation and are sometimes referred to as 'buried placers'. These placers may be buried under (1) volcanic deposits as in California and Australia; (2) glacial deposits as in Canada and U.S.S.R.; (3) talus and other slope deposits; (4) aeolian deposits as in Australia; (5) alluvial sands and gravels; and (6) marine and lacustrine deposits.

There are fossil (lithified) equivalents of eluvial, alluvial, aeolian and beach placers. These are described subsequently.

The gold in auriferous placers may come from one or more of the following sources:

1. Auriferous quartz veins and other types of gold-bearing deposits mentioned in the section on epigenetic deposits.
2. Auriferous sulphide impregnation zones, porphyry copper deposits, etc.
3. Auriferous polymetallic deposits.
4. Slightly auriferous quartz stringers, blows and veins in schists, gneisses and various other rocks.
5. Various slightly auriferous minerals such as pyrite and other sulphides in graphitic schists and other rocks.
6. Slightly auriferous conglomerates, quartzites and other rocks.
7. Old placers.

It should be noted that the geological history of productive placers is frequently complex, much more so than the sequence: primary vein or lode source → eluvial placer → alluvial placer. Often an intermediate collector of gold is involved, mainly auriferous conglomerates, quartzites, etc. Fayzullin (1968) emphasizes this point in his papers. He recognizes a number of variants in the lode-placer sequence as follows: (a) lode → deluvial placer → interceptor → alluvial placer, (b) lode → interceptor → alluvial placer, and (c) interceptor → alluvial placer.

The primary agency that produces gold placers is weathering; a process that involves numerous complex chemical reactions that are explained in detail in Chapter IV. Three things may happen to gold in primary deposits: (1) the gangue minerals may be disintegrated and leached away, leaving the gold relatively untouched; the gold may remain in situ in the oxidized zones or pass into eluvial and alluvial placers; (2) the gold may be dissolved and carried far away from the deposits in which case no placers are formed; or (3) the dissolved gold may be wholly or partly reprecipitated on nuclei of gold in the residuum or on similar nuclei as they are moved along in the alluvium of streams, rivers, beaches, etc. The last process is largely responsible for nuggets. The formation of placers is, therefore, a combination of both mechanical and chemical processes working in consort over long periods of time. We shall return to this theme later in the present section.

The mechanical agencies that assist in the transport and winnowing of gold into placers are gravity, the running water of streams and rivers, the agitation of waves along the shores of lakes, seas and oceans, the wind, and glaciers. Gravity is a force that operates in the formation of all types of placers; it is the principal agent that concentrates gold in eluvial placers. The other agents give rise respectively to the following types of placers: stream and river (alluvial) placers, deltaic placers, beach placers and aeolian placers. There are few authenticated aeolian gold placers of any size, and we shall not consider them further except to note that near the outcrops of some of the primary deposits in Australia the wind had blown away the finer detritus exposing coarser material in which gold was enriched in places (Hoover, 1899, Rickard, 1899). Auriferous sand dunes have been recorded by Spurr (1906) in the Silver Peak quadrangle, Nevada. These apparently contain only traces of gold and silver. Placers due entirely to glaciation are, likewise, uncommon, and none of economic value are known to this writer in moraines, kames or eskers. Certain outwash plains, where worked by glacial and postglacial streams may, however, contain low grade placers in some glacial terrains. Winnowing of gold by present-day streams and rivers from glacial sands and till and working of these materials along certain lakes has also led to minor concentrations of gold in many places in Canada and other glaciated countries. All of these types of glacial deposits are mentioned briefly in the alluvial category.

The minerals concentrated in placers include two types – those with low to medium specific gravity (the light minerals) and those with a medium to high specific gravity (the heavy minerals). All of these minerals have three features in common – great physical resistance to mechanical abrasion and comminution, great chemical resistance to solution in surficial waters and a general equidimensional character in their form. The last is of importance since flaky minerals such as molybdenite, scaly gold and specularite are difficult to concentrate in spite of their high specific gravity. Another factor is the degree to which a mineral can exist in a subdivided form and yet remain relatively chemically stable. This is a factor with respect to gold since the metal can exist in almost infinitely subdivided form giving the so-called 'flour', 'float', 'flood' or 'skim' gold. Such gold does not sink readily in sand and gravel and hence is not concentrated to any extent in placers; on the contrary it may be transported hundreds of miles in running water to be deposited over broad deltas or on the floors of lakes and oceans where it is commonly disseminated throughout great thicknesses of sediment. This particular feature is of importance in discussing the origin of the very finely divided gold of deposits such as the Witwatersrand. (*See* the final section of this chapter on the origin of deposits.) Commonly much flour gold accumulates temporarily in streams and rivers on bars on the inside of curves or meanders or in other areas of slack water ('skim bars'). Unless these are recognized they may give an inflated impression of the potential of a placer stream or river. Skim bars are also misleading during geochemical prospecting within a restricted area since they give false anomalies. This aspect is discussed further in Chapter V.

'Moss gold' is flour gold trapped by mosses and other plants along river and stream beds during high water. 'Moss miners' have collected this gold for centuries along the auriferous rivers throughout the world. It is easily recovered by burning the moss.

With skim and moss gold a new 'crop' appears each year after high water in auriferous water courses. This is partly the reason for the adage that 'gold grows in placers'. It is, however, probably not the whole story as will be seen from a later discussion.

The most common minerals with low to medium specific gravity in placers are quartz (S.G. = 2.65), muscovite, amphibole, pyroxenes, tourmaline, garnet, diamond, chromite, rutile, barite, corundum, wad, limonite and zircon (S.G. = 4.5); those with medium to high specific gravities in placers include monazite (S.G. = 5), magnetite, ilmenite, cassiterite, wolframite, scheelite, cinnabar, gold and platinum (S.G. = 22 when pure). A great variety of sulphides and sulphosalts may accompany gold in placers. This writer has seen pyrite (often abundant), galena, sphalerite, arsenopyrite, boulangerite and jamesonite in placers in Yukon Territory and elsewhere. Native bismuth is present in some placers; native mercury in others; and more rarely native arsenic, native silver, arquerite (Ag-Hg amalgam), native copper, native lead (not shot), native zinc, cinnabar, realgar, sperrylite, molybdenite, chalcopyrite, hematite, carbonates, feldspars, kyanite, topaz, spinel, allanite, epidote, sphene, tantalite-columbite and apatite. Some gold placers contain diamonds and other gems such as rubies, sapphires, emeralds, topaz, garnets, etc. Commonly the gems are secondary in value to gold, and in some placers they are so sporadic as to be a curiosity. Certain placer sands and gravels are cemented or coated by limonite, wad or mixtures of these mineral aggregates. These aggregates commonly contain much silica, alumina, titania and other hydrolysate oxides and frequently large amounts of humic material. Placer gravels or sands strongly cemented by limonite and other iron oxides are often referred to as 'cement gravels' in English speaking countries or 'cangalli' in South American countries. A few placer sands and gravels have been cemented by carbonates, silica or clay, and most placers in the permafrost of Canada, Alaska and U.S.S.R. are frozen solid, requiring a complicated procedure to thaw them out in places.

The gold of placers has varied characteristics. The most common habit is as dust that comprises particles ranging from specks the size of the tip of a needle or less to those the size of a flaxseed (in quantitative terms, <0.1–2 mm). Also common are small scales and spangles; less common are nuggets, crystals, wires, leaves, tufts and hairs and arborescent, reticulated, dendritic, filiform, mossy and spongy forms. Extremely finely divided gold (flour, float or skim gold), the bane of the placer miner and geochemist, is common in some placer districts. Some of the largest natural specimens of the metal have come from placers, frequently of the eluvial type. From these have come some of the largest nuggets of gold won by man. The 'Welcome Stranger' found by accident in a cart rut in the eluvium near Ballarat, Victoria, Australia weighed 2516 oz troy and the 'Blanch Barkley' also from Victoria weighed 1743 oz. The Carson Hill nugget found in California topped the scales at 1296 oz. More generally the gold of placers occurs in small flattened scales or grains averaging a few millimetres in diameter or as moderately finely divided particles known as dust averaging a few tenths of a millimetre in diameter. The fineness of placer gold varies greatly and has been studied by many investigators. A survey of the literature indicates that for most placer deposits the fineness ranges from 500 to 999, that is from electrum to nearly pure metal; most placer gold is above 850 fine. The other elements in placer gold are mainly silver, copper and iron (*see also* Chapter II). Vein gold generally has a fineness that ranges from about 500 to 900. There are innumerable references in the literature that refer to the fact that in any particular district the fineness of the placer gold will usually be higher than that in the veins from which the metal presumably came. Lindgren (1933) for instance states that in California the vein gold averages 850 fine whereas the transported placer gold in the Tertiary channels averages 930 to 950. Similarly, the placer gold of Manhattan, Nevada is finer than the lode gold (Ferguson, 1917). In the Carolinas and Georgia the placers and eluvial deposits commonly have gold with a fineness greater than 900 whereas the vein gold is generally much less than this value, in places being as low as 500. Distance travelled and size of the placer gold also seem to be factors in the fineness, the further from the source and the smaller the size of the particles the higher the fineness. These features are difficult to assess in the writer's experience, but they are evidently true according to a number of placer miners who were consulted on the matter. Certainly, flour gold generally has a high fineness. Hill (1915) and Hite (1933*a,b*) gave an average of about 950 as the fineness of the Snake River flour gold. There is much evidence to suggest that most of the gold in gossans and oxidized zones is of greater fineness than that in the primary ores. Fisher (1945), who made a worldwide study of the fineness of gold in various environments, concluded that gold in the oxidized zone is nearly always higher in grade than the primary gold, and this difference varies largely according to chemical conditions and the facilities that exist for removal of the silver in solution, the gold being redeposited close by, or merely left enriched by the removal of the silver. Under conditions suitable for taking gold into solution the gold redeposited, if the concentration of silver remains high, will not necessarily be of high fineness. He went on to state that very high gold fineness is usually the result of oxidation under conditions favourable for the complete removal of silver, e.g., Mt. Morgan, Queensland, and that high fineness is often associated with the oxidation of telluride ores, e.g., Fiji and Cripple Creek, Colorado. Finally, he noted that alluvial gold, being derived from the oxidized ore, is of higher quality (fineness) than the average of the vein gold, and shows an increase in value downstream, due to surface refining action, as the size of the grains decreases.

In Yukon Territory and at Yellowknife, Northwest Territories some of the supergene gold examined by the writer is of great fineness (990), whereas the primary gold is in the range 900 to 950. Another feature of placer gold, first examined by McConnell (1907) in the Klondike, is that the outer parts of nuggets commonly have a higher fineness compared with the inner parts. The writer has examined some of McConnell's samples and others from a number of placers by electron probe, and found that the rim of greater fineness is rarely more than 0.03 mm (30 μ). A rim of relatively pure gold on nuggets seems to be rather general since Johnston and Uglow (1926) found the effect on the gold of the Cariboo of British Columbia; Fisher (1935) in the Morobe goldfield, New Guinea; and Petrovskaya and Fastalovich (1955) in much of the placer gold of U.S.S.R. Ramdohr (1965) also noted the phenomenon in Rheingold; Mustart (1965) in much of the placer gold of Yukon; and Desborough *et al.* (1970) in placer gold from various parts of the United States. Stumpfl and Clark (1965), however, rightly point out that the rind of purer gold on nuggets, flakes and dust is not always present. They noted its absence in gold-platinoid concentrates from placers in southeast Borneo. The rim effect has generally been interpreted as the result of solution of silver, but the writer is of the opinion that it represents the precipitation of gold (and some silver) on gold nuclei. An argument in favour of the latter process is given in a later section on the origin of placers.

It should be noted that the rim effect in placer gold evidently begins during oxidation of the primary deposits, because it is found in gold in the oxidized zones of auriferous deposits and in eluvial deposits. Gold with enriched rims has been observed by a number of investigators in near-surface shallow deposits (mainly Tertiary) in a number of places, and the phenomenon is noticeable in some kurokô ores in Japan. Enriched rims are rare in deep-seated gold deposits in the writer's experience. In the oxidized ores and placer deposits the rims are generally much wider and better developed than in the primary deposits.

Placer gold commonly contains many inclusions usually small in size (0.005–0.50mm). The inclusions as seen in polished sections and under the microprobe include various sulphides, particularly pyrite, galena and chalcopyrite; also arsenopyrite, various sulphosalts, tellurides and quartz, sericite, rutile, etc., most of the minerals normally found in gold deposits. Many of these minerals are probably original constituents of the gold nuggets since they are commonly near the core of the gold particles. Some often appear as though they were the nuclei about which gold precipitated in the oxidized zones of the deposits. These inclusions should receive detailed study during geochemical prospecting surveys since one might be able to divine the exact source of the gold, especially if material from a few primary sources in the district under investigation is available for control purposes.

Other internal features of placer gold have been extensively studied. In the classic paper by Fisher (1935) the high grade rims referred to above and the general granular structure of the nuggets and flakes are mentioned. Petrovskaya and Fastalovich (1955), who have carried out a long term study of the placer gold of U.S.S.R., also note the nearly universal occurrence of high grade rims and reentrants on gold nuggets and flakes and found that these have a fine-grained polyhedral texture rather than a laminated one as thought by the earlier investigators. They also noted that much of the placer gold retains the internal granular structure and other microscopic features of the primary deposits of gold, but found that much placer gold, especially that held in placers for long periods of time, exhibits marked internal deformation and recrystallization textures. They also observed the presence of intergranular stringers of gold in nuggets and flakes. These were found in the placer gold and in the gold from oxidized zones of auriferous deposits but not in the gold from the primary ores.

The external form, colour, lustre and other features of placer gold visible to the naked eye are commonly characteristic. The miners and bankers in a placer district can generally tell from which creek the gold originated simply by visual inspection. It is said that one banker in Dawson in its heyday could tell precisely from which of the many creeks and gulches of the Klondike a specimen of gold originated, and I am inclined to believe the story having seen gold from all of the creeks either in the old gold room of Yukon Consolidated, Ltd. or in the National Mineral Collection of Canada.

Placer gold usually has an entirely different appearance from that found in veins and other deposits. The high lustre of the vein gold is replaced by a subdued lustre in the placer, due it appears to incipient crystallization on the surface. Some varieties of gold are coloured due to a number of reasons. Black and deep brown gold are commonly due to the presence of coatings of manganese and iron oxides or manganese and iron humates. Alternatively some black and brownish gold is due to a coating of very finely divided colloidal or microcrystalline gold. Whitish and dull greyish varieties of gold owe their colour generally to thin coatings of calcium carbonate, colloidal silica or fine-grained (colloidal) clay. In most placers the gold has the characteristic golden colour, but in others foreign coatings are quite common. 'Black gold' (ouro preto) is very characteristic of a number of placer districts in Brazil and other tropical areas.

The writer has either seen, heard about or read about practically every form of gold in placers and the closely associated oxidized zones of gold deposits. The most common forms are scales, plates and nuggets. In addition some placers contain crystals of gold, hopper-shaped crystallized particles, masses having filiform, reticulated and dendritic shapes and films, wire and mossy gold. The growth forms of large nuggets are commonly fairly regular, many looking like nuts or potatoes; other nuggets are highly irregular and gnarled in shape. Some partly enclose vein quartz fragments or rounded quartz and other types of pebbles and mineral fragments. Some nuggets have unusual growth proturberances that may appear as distorted crystals. A few nuggets have been found that have secondary crystalline outlines.

Various terms are used in the following descriptions to give a semi-quantitative estimation of the size of the gold particles in placers. A 'colour' has no exact meaning; it is used by placer miners to refer to a small piece of gold that usually varies from $\frac{1}{16}$ in. (1.5mm) upward. Estimation of the value of gold colours in a pan and hence of the value of placer grounds can only be gained by experience since the value varies with the size of the colours, their thickness, and their purity. A good estimate can be made by picking out the colours from a number of pans, weighting them on a small pocket microbalance, and calculating the value per yard. There are about 50 pans (18 in. diameter) per yard. Coarse gold (nuggets) is usually considered to be that which remains on a 10-mesh screen (>1.5mm); medium gold will pass a 10-mesh screen and be held on a 20-mesh screen; fine gold passes a 20-mesh screen and is held on a 40-mesh screen (value 1 colour per cent); and very fine gold passes a 40-mesh screen. Flour gold is very much finer than the last; in some places 500 to 1000 colours or more are required to equal the value of a cent!

In general it can be said that the farther that gold has travelled from its source the smaller in size the particles become. Near the source the gold particles are usually rough and relatively large; with distance the particles become smooth, much rounded and smaller. The particles also apparently lose mass with distance from the source. Antweiler and Lindsey (U.S. Geol. Surv. Circ. 622, 1969*b*, p. 6) noted that particles of the Snake River gold, near its source below the outcrops of auriferous conglomerates in Jackson Hole, with diameters approximating 0.125 mm, averaged 10μg in weight, whereas near Twin Falls, Idaho, some 180 mi downstream, particles of the same diameter weighed only half as much. The cause of the mass loss was not discussed.

To summarize this introduction we can say that for the development of placers of any type, four requisites are necessary:

1. The occurrence of gold in deposits, in widespread quartz veins and blows or in a disseminated form in pyritic shales or other country rocks.

2. A fairly long period of deep secular chemical and mechanical weathering on a surface of submature to mature topography, during which time the gold is set free from the deposits or country rocks.

3. Concentration of the gold by some agency, generally water.

4. Absence of extensive glaciation: glaciation does not entirely preclude the occurrence of placers since both eluvial and alluvial types of placers may be overriden and little disturbed by the glaciers in some cases and buried by their deposits of till, clay, etc. in others. Such placers occur in British Columbia, Alaska, Yukon, Quebec and the Lena district of U.S.S.R.

Country kindly to the occurrence of extensive placers is readily recognized. The topography is subdued and marked by broad, often terraced entrenched valleys and rounded deeply weathered hills commonly with nearly accordant summit levels. Few extensive placers are found in terrains marked by sharp alpine features and high gradient V-shaped valleys; similarly, excessively flat terrains far from mountain systems and their foothills yield few productive placers. Like all generalities in geomorphology and geology there are some exceptions to these observations.

The literature on placers is voluminous. Works containing discussions of general principles include those by Liversidge (1893*c*), Weatherbe (1907), Crane (1908), Tyrrell (1912), Longridge (1913), MacKay (1921), Raeburn and Milner (1927), Park (1927), Idriess (1933), Boericke (1933), Lindgren (1933), Gardner and Johnson (1934–1935), Fisher (1935), Crampton (1937), Bilibin (1938), Mertie (1940), Averill (1946), Grutterink (1950), Bateman (1950), Shilo (1956, 1960), Gorbunov (1959), Griffith (1960), Harrison (1962), Vasyunina (1963), Barkovskaya (1963), Trofimov (1964), Fayzullin (1968), Ivenson *et al.* (1969), Shilo and Shumilov (1970, 1976), Valpeter and Davidenko (1970), Romanowitz *et al.* (1970), Volarovich and Shokhor (1970), Kartashov (1971), West (1971), Kazakevich (1972, 1976), Sigov *et al.* (1972), Wells (1973), Denisov (1973), Tayurskii (1973), Kogen *et al.* (1974), Kushnarev and Kashcheev (1974), Tishchenko and Tishchenko (1974), Segerstrom and Ryberg (1974), McLellan *et al.* (1974), Saks (1974, 1975), Vorob'yev and Krapivner (1975), Clift (1975), Prokuronov (1975), Smirnov (1976), Kisterov (1976), Fricker (1976) and Zhelnin and Travin (1976).

The references by Gardner and Johnson (1934–1935), Romanowitz *et al.* (1970), West (1971), Wells (1973) and Fricker (1976) contain up-to-date summaries of the procedures for the prospecting, sampling, evaluation and working of placers. It need hardly be emphasized here that the processes involved in the concentration of gold in placers are extremely complex, and the conditions that control them so variable that even under the most favourable circumstances observable, it is generally not possible to estimate the potential of a placer even roughly without detailed sampling, either by pitting, test holes, or deep cuts or trenches.

The distribution of the principal eluvial and alluvial auriferous placer districts of the world is shown in Figure 67. Many of the districts have long been exhausted, some before the beginning of the Christian Era.

Papers and other works describing placer areas in various parts of the world and methods whereby they are worked are included in the Selected bibliography.

Eluvial placers

Eluvial placers[27] are formed in the weathered residuum over or in the immediate vicinity of primary gold deposits of all types. Commonly these placers develop downhill from the outcrop of the primary deposits (Fig. 68). Some are of the nature of talus deposits or fanglomerate facies on mountain slopes or in the debris at the foots of hills and mountains. An unusual type is formed in the depressions of deeply and irregularly weathered terrane (karst topography). Eluvial placers are closely associated with alluvial placers in many districts, the former giving birth to the latter in many places.

The principal mechanism for the concentration of heavy minerals in eluvial placers is the winnowing action of gravity and downhill creep, the latter being essentially dependent on

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[27] Some geologists, particularly in U.S.S.R., classify these placers as eluvial, deluvial and proluvial. By this classification eluvial placers are those whose outlines coincide more or less with those of the primary deposits. Deluvial (scree or talus) placers are those whose upper limit is at or near the primary source and whose downhill front lies at the foot of a slope. Proluvial placers form in the disintegrated debris at the foot of hills or mountains.

Figure 67. Principal unconsolidated (nonlithified) eluvial and alluvial auriferous placer districts of the world. (Many of the districts shown have long been exhausted.)

Contents

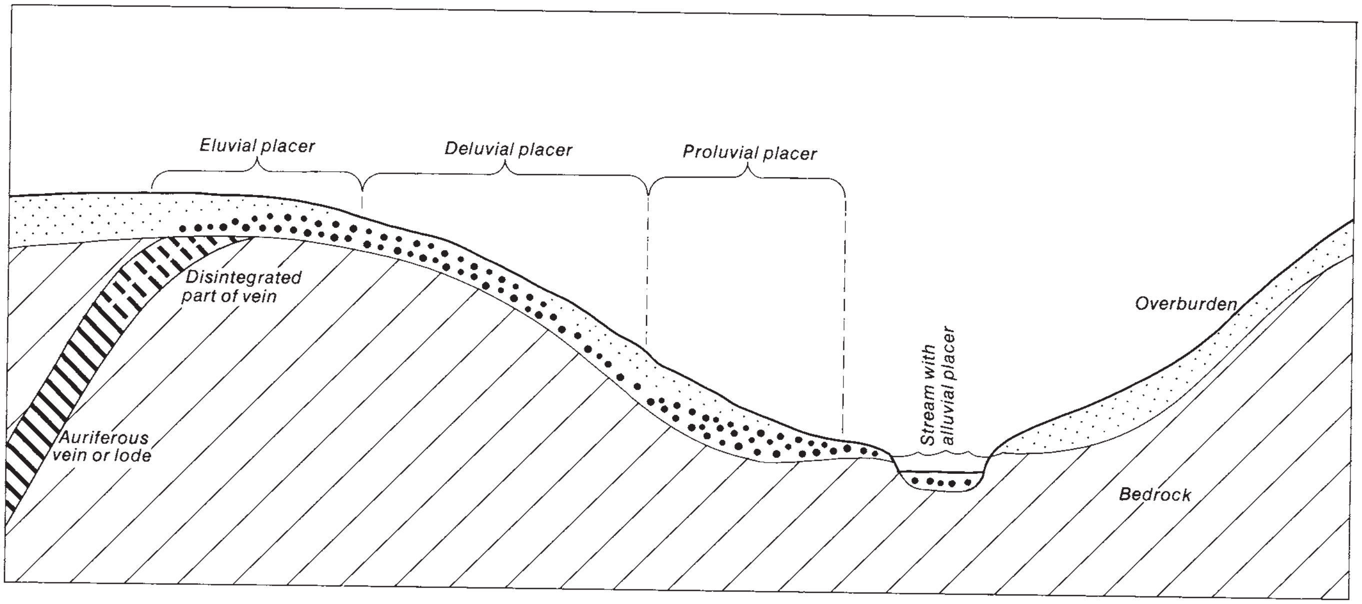

Figure 68. Sketch illustrating outcrop of a gold-quartz vein supplying material to form eluvial and alluvial placers. By one terminology, an eluvial placer embraces all materials not transported by streams. By another, only the placer materials over weathered and disintegrated deposits constitute an eluvial placer; downslope and other placer materials are classified as deluvial and proluvial as shown.

the angle of slope or gradient where the placers are formed on the sides of hills or mountains. Secondary factors include the thickness of the slope materials (scree, talus, residuum), the size and specific gravity of the weathered particles in the residuum, the coefficients of thermal expansion and contraction of residual particles, the coefficient of friction, the movement of ice and snow (glaciers) and the annual and daily variation of temperature. The last governs the freezing and thawing of the residuum in temperate zones, and is particularly important in permafrost regions where solifluction is widespread. Continuous downhill creep appears to be the main way by which gold reaches gulches and creeks. Moving water plays only a small part in the concentration of heavy minerals in eluvial placers, and it is common to find that these placers are largely independent of water courses either in the detritus or on the surface.

Auriferous eluvial placers commonly exhibit considerable gradation and variation in the content and nature of their gold and associated heavy and light minerals. Near the primary deposits the particles of gold are invariably larger and commonly of less fineness than those farther down the dispersion fans and trains on the slopes. During the downward creep of minerals and rock fragments on slopes the lighter fractions tend to gravitate to the top layers and move relatively faster downhill than the heavier fractions. This is why one commonly finds a greater concentration of light minerals and rock fragments such as quartz floats at the foots of hills and mountains rather than farther uphill and at the outcrop of auriferous quartz veins. Finally, nonuniformity and erratic behaviour commonly prevail in the continuity and value of the pay streaks in most eluvial placers, a feature that dictates that most of these deposits must be carefully pitted, trenched, drilled and evaluated before exploitation.

Eluvial gold placers were widely worked in many parts of the world prior to the turn of the century. Most were residual blanketlike deposits developed on a relatively flat terrain, or fanlike accumulations formed on gentle slopes. The materials of these deposits varied greatly depending principally on the types of bedrocks and deposits and the type and degree of weathering. Most had a high iron (lateritic) content although some were relatively highly enriched in aluminum (bauxite or clay). Most consisted of a residuum of quartz, sand, clay, iron oxides, aluminum oxides and manganese oxides in which the particles of gold, commonly with a number of other chemically resistant heavy minerals, were concentrated on or near the bedrock. Some of these deposits are highly cemented with clay, limonite or caliche (carbonates); more rarely by silica. Most eluvial placers are low grade in gold, but some are of enormous yardage (tonnage). Much of the gold in eluvial placers is rough and irregular in form, and the fineness is commonly only slightly higher than that in the primary deposits. Eluvial placers are known for their large nuggets or masses of gold, some weighing several hundred to a thousand ounces or more; alluvial placers only rarely contain large nuggets (>100 oz). Some eluvial placers yield silver, lead, cassiterite, cinnabar, diamonds and platinoids in addition to gold. A few descriptions of typical examples of eluvial deposits follow.

Extensive eluvial placers are unknown in Canada, but there are a number of small examples mainly in Yukon that are of interest from an academic viewpoint. In the Dublin Gulch area, Yukon (Boyle, 1965*a*), small eluvial placers are developed on the sides of the hills above the economic gold placer in the gulch (Fig. 69). The eluvial placers contain mainly scheelite with small amounts of wolframite and gold, these minerals being derived from a complex of scheelite-

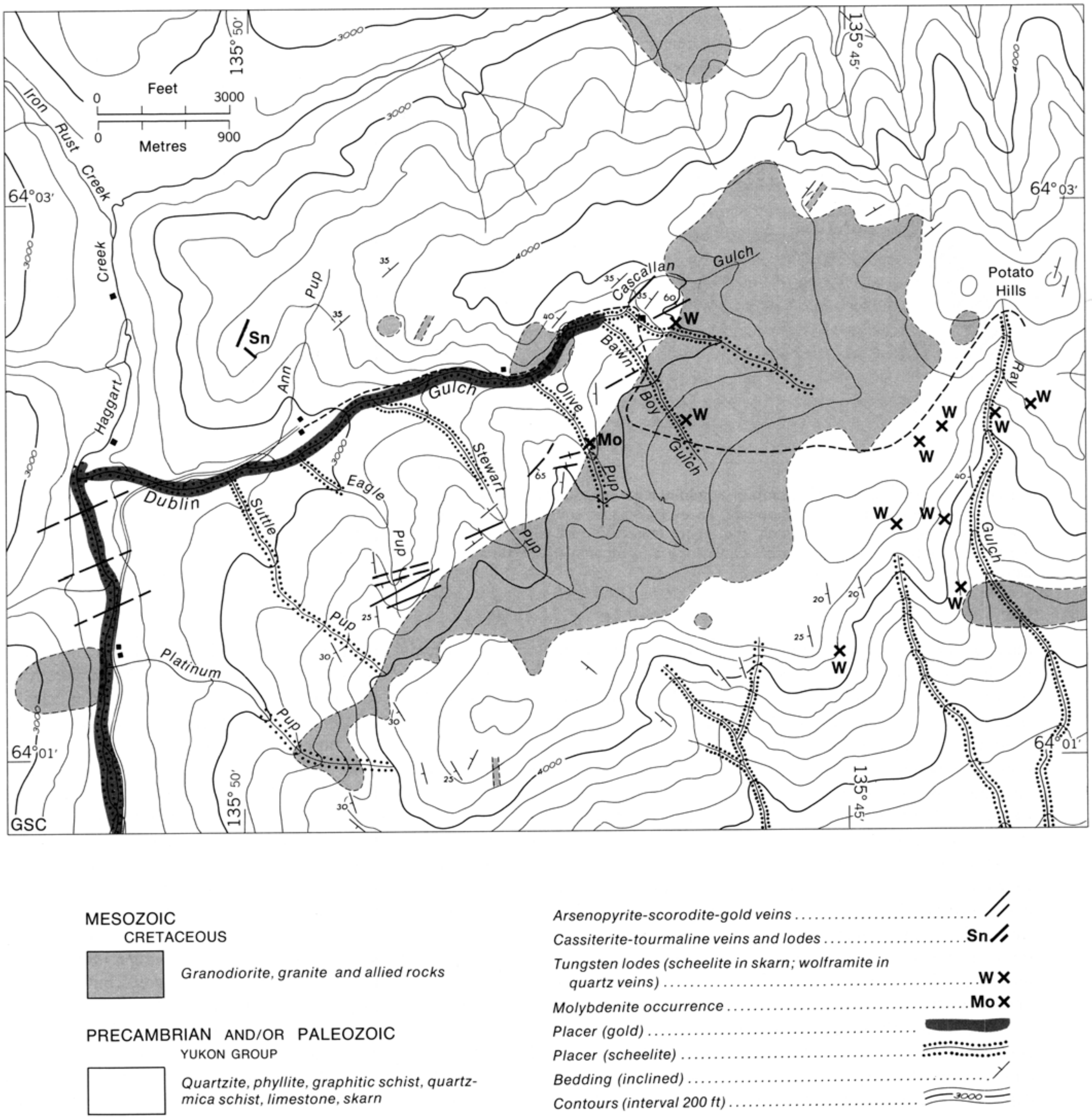

Figure 69. Generalized geology of Dublin Gulch area, Yukon showing gold and scheelite gulch placers (after Boyle, 1965*a*).

bearing skarn, quartz-wolframite veins and northeast striking quartz-arsenopyrite-pyrite-scorodite-gold veins, all lying slightly uphill from the eluvial placers. The constitution of the eluvial material is varied depending on the type of bedrock. Over schists the materials are mainly mixtures of sand, clay, limonite and disintegrated schist; over granodiorite the materials are principally a limonitic clay mixture with highly disintegrated feldspar and quartz. The principal heavy minerals in the eluvium are gold, scheelite, wolframite, extrinsic hematitic nodules of iron-formation, garnet, cassiterite, magnetite, bismuth, pyrite, arsenopyrite, jamesonite, siderite, nodules of oxidized galena, limonite, wad and scorodite. Eluvial material containing gold and scheelite is greatly enriched in arsenic, antimony and tungsten a feature that can be used in geochemical prospecting for this type of deposit.

In the western United States eluvial placers have been worked in the past in California, Oregon, Nevada and Montana, but few rivalled the alluvial types in these states in their economic importance. In the Appalachians of the United States eluvial placers were worked on a fairly large scale before the turn of the century, especially in Georgia, (Becker, 1895; Pardee and Park, 1948; and Lesure, 1971). There, in the Dahlonega gold belt in Lumpkin County, the bedrock is a complex of mica schist, mica gneiss, quartzite, amphibolite, migmatites and granite. The schists contain abundant gold-bearing quartz veins and stringers of various ages. All rocks and deposits are deeply weathered forming at the surface what has been called a saprolite by Becker (1895). Saprolite is in reality only a form of laterite; it is brownish in colour, composed of soft, earthy, clay-rich materials derived from thoroughly decomposed schist and other metamorphic rocks. Zones of disorganized and disintegrated quartz veining in the saprolitic schists were mined by deep open cuts on a large scale near Dahlonega, the gold being won partly by washing and partly by crushing of the quartz in stamp mills. The enrichment in the saprolite was evidently due to considerable leaching and precipitation of gold as suggested by the geochemical results quoted by Lesure (1971), who found up to 2.9 ppm in freshly precipitated limonite. The gold distribution in the fresh vein quartz is low and spotty, and the primary deposits are apparently not attractive mining ventures.

Certain gossans on stockworks or massive sulphide deposits and their attendant eluvial deposits have been mined or are being mined for gold. At the Greenhorn Mine in Shasta County, California an auriferous gossan was worked profitably for many years (Huttl, 1940). The gossan was developed on a copper sulphide orebody and consisted of a mass of limonitic material of varying thickness containing localized zones of rhyolite. The principal values in the gossan were gold and silver with some flakes of native copper. The gold particles were extremely fine, almost microscopic. The combined gold and silver content averaged about 0.20 oz/ton. Similar gossans have been mined in many countries, e.g., Spain (Rio Tinto), Australia (Mt. Morgan) and elsewhere. Some of these are described in more detail in Chapter IV.

Eluvial deposits have been worked in many places in the lateritic residuum in Mexico, Central America, Cuba, Haiti, Puerto Rico and the countries of South America.

In Mexico eluvial-alluvial placers in three large fans of gravels downslope from a mineralized porphyritic granite stock and its limestone contact zone are found near Guadalcázar in the central part of the State of San Luis Potosi (Fries and Schmitter, 1948). The placers were derived from the weathering and erosion of the mineralized parts of the granitic body and its contact zone and contain tin as cassiterite, mercury as cinnabar and minor amounts of gold and silver. The gold in the finer fraction of the gravels and sands is free; in the coarser fractions it is chiefly in sulphide minerals (pyrite, arsenopyrite, galena, sphalerite, stibnite, silver sulphosalts) and their oxidation products. Part of the silver is in sulphides and sulphosalts and a part is alloyed with the native gold. Average assays of some of the placer materials show the following: 84 ppm Sn, 15 ppm Hg, 9.44 ppm Ag and 0.058 ppm Au. Some 550 million m^3 of gravel are present in the fans.

In South America most of the eluvial deposits were blankets and eluvial fans in the lateritic materials near zones of quartz veining in Archean greenstones and associated sediments. In actual fact gold in the laterites of the Guianas is widespread ranging from 0.003 to 0.135 ppm over hundreds of square miles in some places. Such areas seem to be centred on auriferous Precambrian greenstone and sedimentary belts intruded by granitic rocks and porphyries. During weathering, therefore, gold has apparently been concentrated in the laterites both from the rocks and from epigenetic gold-bearing deposits. Extensive natural winnowing of the laterites has evidently given rise to the important alluvial placers, which are a feature of the Guianas. One interesting deposit at Omai, Guiana (British Guiana) was a deeply weathered aplite dyke highly decomposed to a depth of more than 100 ft (Maclaren, 1908). The primary dyke material was shot through by slightly auriferous quartz stringers and heavily pyritized, the pyrite being auriferous. The decomposed material consisted essentially of limonite-stained sand and clay, in which well crystallized free gold was abundant.

Other interesting types of eluvial deposits occur in Brazil mainly in the Quadrilátero Ferrífero, Minas Gerais. All of these are associated with gold-bearing iron-formations (itabirites). General descriptions of these deposits are given by Derby (1884, 1903), Bensusan (1929), De Oliveira (1930, 1932), Gair (1962) and Dorr (1969) (*see also* p. 304 of this chapter). One type of secondary deposit, not necessarily eluvial, but often grading into eluvial deposits is locally known as "jacutinga" (De Oliveira, 1932). The jacutinga occurs as thin (inches to a few feet) lines or bands in itabirite and is a decomposition, or more accurately a surficial chemical disintegration product of the iron-formation. It is composed essentially of powdery ferric oxide (limonite and hematite) manganese oxides, clay minerals and talc in which nuggets, plates and threads of native gold are present. Evidently the gold originated by chemical solution and reprecipitation of the metal, from low grade gold-bearing iron-formation. From the descriptions, some of the jacutinga were rich, up to 0.5 oz Au/ton or more, and some were mined to depths of 700 ft. Some of the gold was rich in palladium.

The other type of deposit associated with iron-formations in Brazil is the gold-bearing 'Tapanhoancanga' or 'Canga' for short. This is an irregular layer or blanket up to 10 ft or more thick of limonite-cemented fragments of iron-formation (itabirite). It is commonly developed on all iron-formations throughout the world that are extensively oxidized. Much of the limonite appears to derive from the oxidation of iron silicates and pyrite in the iron-formation. Where the iron-formations are also gold-bearing the canga is commonly enriched in gold, the metal occurring in small flakes, wires, specks and also in a submicroscopic form associated in some manner or other with the limonite. In the past, deposits of this type were worked in a small way in many parts of the ferriferous quadrangle in Minas Gerais.

Eluvial placers have not been important sources of gold in Europe although they have been worked in the past, some by the Romans, in Portugal, Spain, France, Switzerland, Germany and Romania. Important eluvial deposits were once worked in the Berezovsk, Kochkar and other districts in the U.S.S.R. In Africa a few eluvial placers have been worked mainly in Egypt, Sudan, Ethiopia, Zaire, Ghana and elsewhere in the western gold belt of Africa. Most were small but have mothered extensive alluvial placers in a number of countries. It is of interest to note that the great Rand deposits of South Africa gave rise neither to extensive eluvial nor to alluvial deposits, a feature that is difficult to explain. The reason for the paucity of placer gold associated with these enormous deposits probably has much to do with the size of the gold in the reefs (50 μ) and the presence of abundant pyrite, which weathers readily to give soluble iron salts and colloidal hydrous iron oxides. Both of these features would tend to render the gold soluble or mobile as an absorbed component, thus ensuring its broad dispersion.

Eluvial gold was relatively common in Australia before the turn of the century, but most of these placers are now exhausted. Fabulous nuggets were found in some districts in the eluvium or weathered rubble of the oxidized deposits. At Big Nugget Hill in the Hargraves goldfield of New South Wales a nugget weighing 106 lb was found in the eluvium by an aboriginal shepherd. At Lucknow, also in New South Wales, the eluvium was of great richness at and near the outcrop of the veins. In Victoria even larger nuggets were found in the eluvium and disintegrated country rock near the veins of Ballarat, Tarnagulla and other places, including the Welcome Stranger (2516 oz), Welcome (2195 oz), Blanch Barkley (1743 oz), Canadian (1319 oz), Dunolly (1364 oz) and Sarah Sands (755 oz). In Western Australia the eluvial placers were small, rich and soon worked out in the Pilbara, Kimberly, Coolgardie, Kalgoorlie and other Yilgarn fields.

In Asia eluvial gold has been won from soils and weathered debris near outcroppings of gold in Japan, China, Burma, India, U.S.S.R. and elsewhere. Most of these deposits were small and have long been exhausted. One type of eluvial deposit in U.S.S.R. is of considerable interest both economically and scientifically – the Kuranakh type. The Kuranakh gold deposits found in 1959–1962 are mainly in Lower Cambrian bituminous limestones and dolomites in the Aldan anteclise of southern Yakutia (Razin and Rozhkov, 1963, 1966; Kazarinov, 1969; Borodaevskaya and Rozhkov, 1974). There is considerable similarity between the primary gold occurrences and those described in this chapter for the disseminated deposits of north-central Nevada (Carlin, Cortez, etc.). The primary occurrences in the Kuranakh district are mainly potash feldspar (adularia) and quartz metasomatites with about 6 ppm gold occurring as irregular replacements of the limestones and dolomites in places in stratiform bodies up to 3 km in length, 300 to 500 m in breadth and 5 to 10 m in thickness. The gold in the adularia zones is very finely-divided (2–5 μ) and mainly in pyrite. Thin kersantite dykes and sills of late Mesozoic age are also accompanied by adularization along their contacts both in the Cambrian strata and in Lower Jurassic sandstones, and these igneous rocks have a comparable tenor of gold within the ore zones. Oxidation of the primary gold-bearing zones and karstification of the Lower Cambrian limestones in post-Jurassic and Recent times has given rise to economic eluvial deposits consisting essentially of highly weathered material composed mainly of oxidized ore, limonite, clay and sandy materials in the karst cavities (Fig. 70). The gold in the eluvial material occurs as very finely-divided flakes ranging in size from 5 to 20 μ. The ratio of concentration is not given, but presumably it is about 2 making the grade of the deposits about 12 ppm (0.35 oz Au/ton).

In Luzon, Philippines, eluvial placers are common and were extensively mined in the past. Gilbert (1940) describes a number of these from the Paracale-Mambulao district where the primary auriferous material is mainly veins and stockworks of quartz and pyritic quartz veins in granite intruding serpentinites. The auriferous eluvial material consisted mainly of weathered debris and disintegrated bedrock carrying free gold.

Certain eluvial auriferous deposits take the form of talus accumulations. A typical example of this type of placer occurs near the Belaya Gora deposit in the Lower Amur region of U.S.S.R. (Borodaevskaya and Rozhkov, 1974). The bedrock deposit occurs near the summit of Belaya Gora in a strongly fractured, kaolinized and silicified Oligocene volcanic neck. The gold is mainly free and accompanied by about 0.5 per cent combined pyrite, arsenopyrite, sphalerite and argentiferous sulphosalts. The talus placer associated with the primary deposit lies below the deposit on a gentle slope and averages some 5–6 m in thickness. In composition the talus material is largely variegated clay and sandy clay and oxidized rubble with a heavy mineral suite composed mainly of limonite, magnetite, ilmenite, chromite, epidote and small amounts of zircon, sulphides, manganese oxides and other minerals. The gold is disseminated through the talus material and also forms short streaks and enriched lenses. The gold in the talus is not much different from that in the bedrock. The gold grains range in size from 0.05 to 1.5 mm. Some adsorbed and very finely divided gold also occurs in concretions of kaolinite and quartz. Downhill from the talus placer there is a colluvial and alluvial placer system associated with springs and the river fed by the springs.

Alluvial placers

Alluvial placers are those formed in present and past water courses in gulches, creeks, rivers, flood plains and deltas. Reworking of some of these deposits together with others formed as a result of sedimentation or glacial processes by wave action may yield beach placers, which are treated separately.

Alluvial placers have been worked since ancient times in practically every country (Fig. 67) and have produced probably about one-quarter of man's store of gold. If we include the

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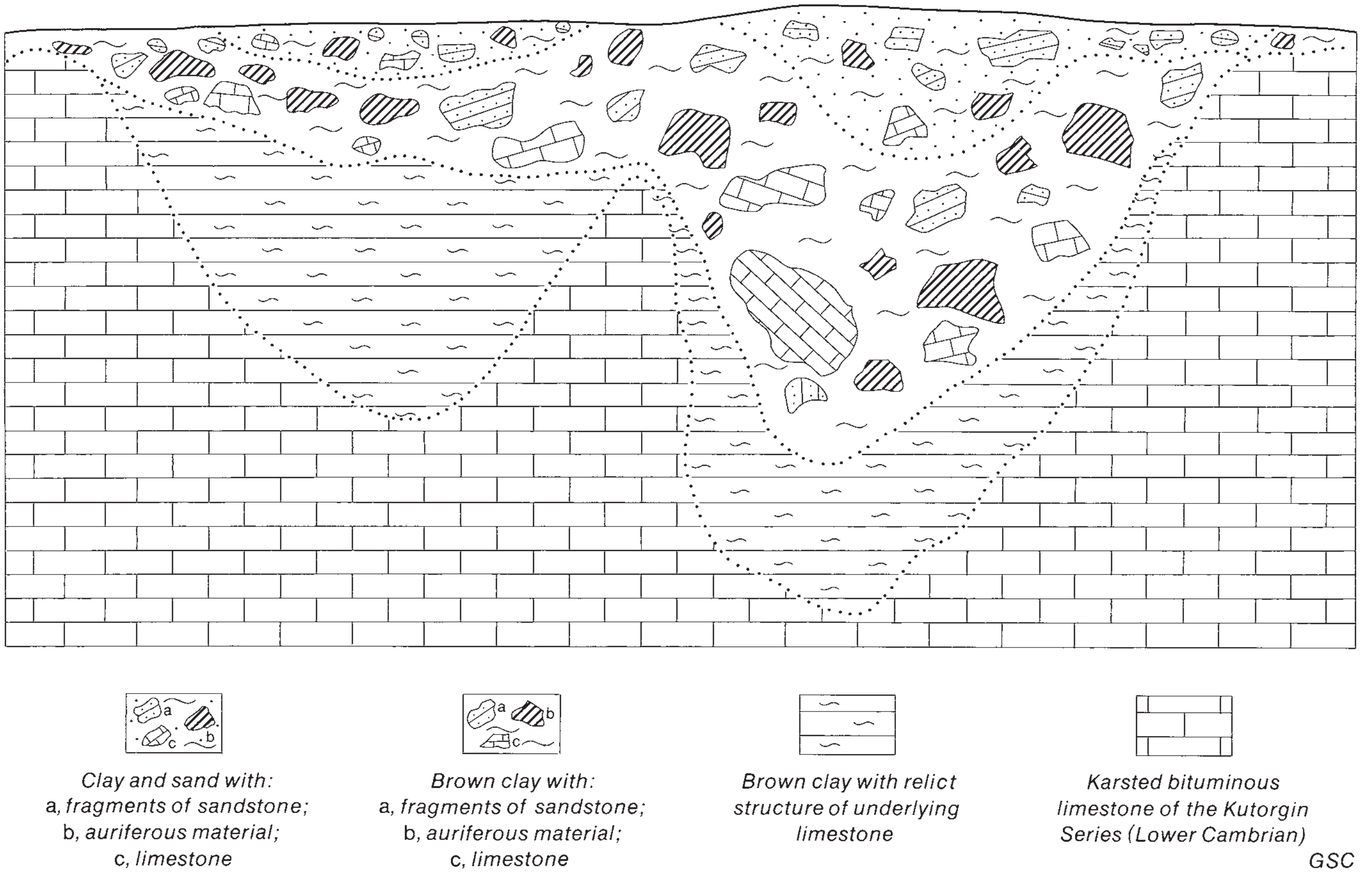

Figure 70. Schematic cross-section of an auriferous karst, Kuranakh district, southern Yakutia, U.S.S.R. (after Razin and Rozhkov, 1963). (No scale given on original.)

Witwatersrand deposits as fossil alluvial placers, the amount of gold produced from these types of placers probably approaches two-thirds of man's store of the precious metal.

Alluvial placers can be classified into two general categories – modern and fossil. The distinction between the two is commonly difficult to make in the field. Placers formed in present day water courses and most of those of Pleistocene and Tertiary age fall into the modern category. Those of greater age, commonly buried deeply by superincumbent sediments or volcanics and generally lithified we shall call fossil. Fossil placers occur throughout the geological column and are described subsequently.

There is an enormous amount of literature on alluvial gold placers, dealing with descriptions of the placer fields, the principles of placer formation and the methods of panning, rocking, sluicing, hydraulicking and dredging. The interested reader is referred to the general references mentioned in the introduction to the section on placers.

There are some general characteristics of alluvial gold placers that will serve as a basis for the descriptions and discussion that follow. These include: alluvial placer gold in pay streaks near its source is invariably coarse and is found in the lower layers of the alluvium either on bedrock, in a zone a few feet above the bedrock or in crevices, fractures, etc. in the bedrock within a few feet of the surface. An exception to this is where the so called 'false bottoms' or 'false bedrocks' occur in thick beds of alluvium. These false bottoms may be clay layers (hard pans) within the gravels, compacted sands or more rarely limonite-cemented sands and gravels (conglomerates). Alluvial placer gold far from its source is generally finely divided, and while part of the gold may be on or near bedrock or false bottoms most of it is dispersed throughout great thicknesses of the sediments. This is especially true of extensive flood plain and deltaic deposits. Two other features are characteristic of most alluvial gold placers. The first, as intimated above, is that the further from the source the more finely divided the gold, and the second is that placer gold is finer in value than its source lode gold and that with increasing distance from the source the finer is the gold. These two statements are general. The first is invariable, but there are exceptions to the second in some districts.

Alluvial placers are composed of loose unconsolidated gravels and sands that are commonly relatively clean. The terms 'white channel gravels', 'white leads' and 'white bars' reflect the latter circumstances with respect to quartz. In places, however, the pebbles and the gold may be coated with limonite, wad and other precipitates. Some alluvial gravels and sands are heavily impregnated with limonite and wad forming the 'cement gravels' or 'cangalli' of the alluvial miner. Such gravels invariably occur where the primary deposits and wall rocks are rich in pyrite, siderite, chlorite and other iron- and manganese-bearing minerals. Secondary siliceous and calcareous cements are rare in alluvial gravels except in the vicinity of siliceous springs and lime-bearing waters; some alluvial deposits may be cemented by caliche in arid regions. In permafrost zones the alluvial gravels are frozen solid and have to be thawed out before dredging or hydraulicking.

The heavy mineral suite accompanying gold in alluvial placers differs depending on the host rocks and types of primary deposits. Magnetite and ilmenite are the most common, and these may be accompanied by varying amounts of monazite, pyrite, arsenopyrite, cassiterite, wolframite, scheelite, cinnabar, native bismuth, bismuthinite, galena, sulphosalts, platinoids, tourmaline, garnet, chromite, rutile, barite, corundum, zircon, wad and limonite.

Most alluvial deposits in gulches, streams and rivers are characterized by a lack of regular and persistent bedding or stratification, but pseudobedding, laminations, current or false bedding may be developed in some accumulations. In deltaic deposits bedding and stratification is poorly- to well-developed depending upon the rate of sedimentation. Fractures, fissures and even faults can be seen in some modern alluvial placers. The last may throw the pay streaks several tens of feet in places.

Gold placers can be classified in a number of ways based upon their location or genesis. Kartashov (1971) gives a classification that is current among some placer geologists in the Soviet Union. He distinguishes two types of alluvial placers – autochthonous and allochthonous (Table 66). In the authochthonous variety he lists those placers formed essentially near the primary or more rarely the secondary source(s) of their gold; the allochthonous variety implies considerable transport of the gold and deposition far from the primary and/or secondary source(s). This classification is quite satisfactory but requires a considerable knowledge of the details of placer deposits and the dynamics of their formation before they can be adequately categorized. Another classification of placers is provided by Kazakevich (1972) (Table 67).

The simplified classification of placers adopted here follows essentially the scheme suggested by Lindgren (1933) and others based mainly on the geological location and the tectonic history (uplift and depression) as shown in Table 68. The latter factor is emphasized by Trofimov (1964), who considers it to be the chief control on the formation of placers.

The formation of alluvial placers depends upon many interacting physical and chemical factors, our general knowledge of which is fairly well established. However, our understanding of many of the chemical and physical details of the accumulation of gold in alluvial placers is still remarkably poor, especially with respect to the formation of nuggets. There are also many differences of opinion as to why gold is concentrated on or near bedrock in alluvial placers. These problems are discussed subsequently.

The physical and chemical factors involved in the formation of alluvial gold placers are: an adequate source of primary gold, favourable oxidation processes for its release

Table 66. Characteristics of the kinds of alluvial gold placers

	Autochthonous		
Notes	Bottom*	Above-bottom*	Allochthonous
1. Are represented by	Channel, valley, terrace and watershed placers	Valley, terrace and watershed placers	Point-bar delta, river-plain, valley, terrace and water-shed placers
2. Occur	Adjacent to their gold-bearing sources		More or less far from their gold-bearing sources, being separated from them and from autochthonous placers by zones of dispersion of 'placer' minerals
3. Are concentrated	At the base of an instrative† or substrative† alluvium and in the crevices of the bedrock	At the base of a perstrative† alluvium and within constrative† strata, in the same parts of valleys as bottom placers	In surficial horizons of a perstrative alluvium and within constrative strata, downstream from autochthonous placers
4. Consist of mineral grains	Derived directly from gold-bearing sources or redeposited from older placers and not carried away by rivers from concentration zones		Brought by rivers into concentration zones
5. Accumulate during	Entire time of destruction of primary gold-bearing deposits, embracing, as a rule, many stages of river development	The last equilibrium and/or aggradation stages of river development	
6. An enclosing alluvium is formed during	Downcutting stages or transition from them to equilibrium stages	Equilibrium and/or aggradation stages	
7. An enclosing alluvium, being reworked during a downcutting stage, is	Not destroyed but displaced to the level of a new bedrock bottom	Displaced to the level of a new bedrock bottom and added to bottom placers	Completely destroyed
8. The mechanism of concentration of 'placer' minerals	Does not essentially depend upon the hydrodynamic properties of flowing water		Depends to a large extent upon the hydrodynamic properties of flowing water

Adopted from Kartashov (1971).

*These terms refer to the position of the pay streaks with respect to the bedrock.

†Instrative, perstrative and constrative correspond to the stages of river downcutting, dynamic equilibrium and aggradation. Refer to Figure 73 and the original article by Kartashov (1971).

Table 67. Genetic classification of gold placers

Type	Sub-type
I.Eluvial	1. Zones of weathering of gold-quartz deposits
	2. Zones of oxidation of auriferous sulphide deposits
II.Slope	1. Solifluction and land slide placers
	2. Solifluction and deluvial placers
	3. Deluvial and landslide placers
III.Watercourse	1. Alluvial placers
	2. Proluvial placers
	3. Lacustrine placers
IV.Glacial	1. Placers of main and lateral moraines
	2. Placers related to interglacial and glacial streams and other water courses of glacial origin
V.Eolian	Placers in eolian sands
VI.Marine	1. Beach placers
	2. Placers on underwater slopes
	3. Placers in near shore still water (lagoons, coves)

Source: Kazakevitch (1972).

Table 68. Classification of alluvial placers according to their geological location and tectonic history (uplift or depression)

Present form	Elevated equivalents	Depressed equivalents
1. Gulch, canyon and creek gravels	High level gulch and creek gravels	Deeply buried gulch and creek gravels
2. River and bar gravels	Bench gravels High level river and bar gravels	Deeply buried river and bar gravels
3. River flood-plain gravels	High level flood-plain gravels	Depressed (deeply buried) flood plain gravels
4. Deltaic gravels	Elevated deltaic gravels	Depressed deltaic gravels
5. Beach and shore line gravels	Elevated beach and shore line gravels	Depressed beach and shore line gravels

and favourable concentration sites, all of which depend essentially on the tectonic environment, which controls the dynamics of streams and rivers. Each of these is discussed below.

1. Nature of the oxidation processes in the primary gold-bearing deposits: several factors are involved, including climatic and groundwater conditions and the nature of the primary gold, gangue and wallrocks. These are discussed in detail in Chapter IV. The nature of the primary gold and the chemical system operating during oxidation of the deposits are two critical factors in the formation of alluvial placers.

The size of the primary gold particles is a major consideration. Where the particles of native gold in a primary deposit exceed 100 μ there appears to be relatively little solution or flotation of the gold in the natural waters. During oxidation processes the particles tend to go directly into the eluvium and creep from there into the alluvial placers. They may, however, accrete gold from the soil solutions and stream waters as they proceed on their journey.

In some districts, however, where the primary gold is extremely finely divided (<50 μ) or is a microscopic or lattice constituent of auriferous pyrite, arsenopyrite, tellurides, etc., alluvial placers are not formed to any extent even though other conditions are favourable. One striking example of this is the paucity of alluvial placers associated with the great Witwatersrand deposits. In such districts the gold does not seem to aggregate to form large particles. On the contrary it appears to be dispersed as flour gold or is dissolved and dispersed throughout the ground and surface water systems. In other districts the reverse situation exists, and alluvial deposits abound even though the gold is finely divided or a constituent of pyrite, etc. in the primary deposits. In these the gold accretes mainly in the oxidized zones and eluvial deposits to form relatively large particles, which ultimately find their way into the alluvial placers. To explain the difference in behaviour between the two extremes is not simple because of the complex chemical systems involved. In the writer's experience one important factor appears to be the purity of the finely divided primary gold. If its silver and/or copper content is high the gold appears to be more readily dissolved. This is understandable from etching procedures in microscopic work on gold – pure gold etches with great difficulty whereas alloyed gold is readily etched. Once dissolved the gold may be dispersed or reprecipitated (accreted) depending on the chemical system, especially on the Eh and pH of the environment and the presence of various colloids and precipitants (*see* Chapter IV). The relatively pure, finely divided gold, on the other hand, enters the erosion cycle chemically unaffected and is mechanically dispersed far and wide. Finely divided gold contained within pyrite and arsenopyrite and lattice gold in these minerals and in tellurides, aurostibite, etc. tends to accrete and form large particles, wires, etc. for reasons that are obscure but which may involve the solvent effects of thiosulphates, cyanides and ferric sulphate, interaction of the dissolved gold with natural reductants and various colloidal reactions. The surface characteristics of finely divided gold also seem to be important in its mechanical transport in water and probably also in its dissolution in oxidizing solutions. Some finely divided gold particles appear to have a relatively small contact angle due probably to films of organic substances, which permit air bubbles to attach themselves readily, a feature that promotes their easy flotation downstream. In the case of the Witwatersrand gold the film in some cases may be the hydrocarbon (thucholite) with which the gold is intimately associated. Films of all kinds, including both organic and inorganic substances, commonly inhibit the solution of finely divided gold in natural solutions. The most common inhibitors appear to be the various hydrous iron and manganese oxides and silica.

2. Nature of the bedrock or false bottoms: since alluvial gold is invariably found on or near the bedrock surface or on false bottoms the characteristics of these substrates are commonly decisive in the formation of alluvial placers. Few 'pay streaks' or 'runs of gold' occur on smooth bedrock bottoms for obvious reasons. The most favourable bedrocks are those that form natural riffles perpendicular to the stream or river course as in a gold sluice. Alternating thin beds of soft schist and hard quartzite or slate and quartzite are particularly favourable. It is a surprising fact, however, that in some placer areas bedrock riffles parallel to the direction of the stream flow are

more effective in trapping the gold than those crossing it at a large angle. Limestone bedrocks that are pitted and pinnacled provide particularly good settling places for gold, as do potholes and nests of boulders in some placer streams. Partly weathered schists and gneisses in which the leaves of the schist and bands of the gneiss are slightly separated are also ideal rocks for the concentration of alluvial gold. The little nuggets, flakes and specks of gold dust work their way into such rocks often to depths of 10 ft or more. Similar phenomena are noted where the bedrocks are sheared, fractured or intensely shattered. Limestones in karst terrane are also good traps for gold, the metal having worked its way down into the rock to depths of 30 or 40 ft in some placer areas. Mining of these zones of enriched bedrock is common in many alluvial gold districts. As for false bottoms, indurated clay and hardpan layers appear to be particularly favourable, although rough gravels and sands cemented by limonite, wad or carbonate provide suitable surfaces for the accumulation of gold in some districts. Compacted sands with rough surfaces are favourable in others. Some placer areas are characterized by stacked pay streaks due to alternating bands of clay, compacted sand, etc. in the sedimentary section.

3. Stream and river dynamics: this subject is complex involving hydrodynamics, sedimentation phenomena, geomorphology and isostasy (uplift and subsidence), subjects that can be treated only in a general manner here.

It is assumed that the reader is familiar with the general rudiments of the principles of sedimentation of falling bodies in static water. Briefly, the controlling factors involved are mainly the differences in specific gravity, size and shape of particles. It is axiomatic that of two spheres of the same weight but of different size, the smaller, with its lesser surface area, and hence lesser friction to water, sinks more rapidly in a static water medium. This is part of the reason why gold as small nuggets is commonly associated with quartz pebbles 1 in. or more in diameter.[28] Furthermore, the shape of particles is a factor – a spherical mineral has less surface area than a platy mineral of the same weight and hence sinks more rapidly. Finally, during jigging of bodies of variable specific gravity in water, those with the higher specific gravity sink to the lowest level. During this motion, round, shotty particles of gold will also find the bottom quicker than scaly or spongy particles.

We are, however, not generally dealing with static bodies of water in the formation of placers but with bodies of water that move and exhibit turbulent flow. The principal parameters in stream and river dynamics are the gradient and the volume of water. The gradient is determined by many secondary factors in an area but fundamentally by isostasy, which involves uplift (or depression) of one segment of the earth with respect to the other. The volume of water delivered to a stream or river, likewise, depends on many secondary factors involving the runoff and groundwater systems but primarily on the rainfall of the district. In a district with a pluvial climate once a gradient has been established stream and river systems develop that erode the land and yield a pattern of gulches, canyons and valleys.

The dynamics of the movement of sedimentary particles in streams and rivers are of interest in the formation of placers. The factors involved are many, including the velocity of the water, which depends essentially on the gradient; the degree of turbulent flow, the specific gravity of the minerals being transported and the nature of the stream or river bed. Two types of solid load transported by streams and rivers can be distinguished – the suspended load and the bed load. The suspended load is maintained in the body of water mainly by turbulence, although flotation of sedimentary particles attached to air bubbles may be important in places. The bed load consists of material that is rolled, pulled, slid or otherwise swept along the bed of the stream by traction or saltation (skipping of pebbles along the bottom in a series of leaps). In addition to these movements there is a constant creep of the sediment down gradient. This effect is small where the slope is minor, but may be marked where high gradients prevail. As an approximation it is said that the transporting power of a stream varies as the sixth power of the velocity. Calculations show that a stream running 2 mph (3 ft/sec) will carry a stone or nugget weighing about 3 oz; at 4 mph one weighing 45 lb; at 10 mph one weighing 1.5 tons; and so on. It is easy to understand how a spate of water moving down a gulch at 20 mph, as during flood times, can move boulders weighing 100 tons and more.

The evolution of a landscape following a general uplift above sea level follows definite patterns depending essentially on the amount of rainfall received. In districts with humid climates most rivers flow into the oceans, although interrupted in places by lakes. Four normal stages of evolution of drainage systems in humid areas can be recognized – initial, youthful, mature and old age. During the initial stage the gradients are low, depressions become filled with water, and streams lazily follow various gulleys and flaws in the rock. The rate of erosion is minimal, and few if any placers are formed. As the youthful stage sets in an integrated pattern of major streams with numerous tributaries develops by downward and headward up-gradient erosion, most lakes disappear and V-shaped valleys, and in places steep gulches, canyons and gorges, mark the landscape. With time the normal evolutionary pattern develops further to maturity. Gulch, creek, stream and some river placers are characteristically developed during these stages. As the rivers erode down toward their base level, lateral erosion develops wider and wider valleys with gently sloping sides, flood plains are formed, and meandering courses that wander hither and thither from channel to channel are characteristic. Some creek and stream placers continue to develop, but river, flood plain and deltaic placers are the mark of this stage. Continued slow downcutting of rivers and streams or uplift may leave the remnants of earlier valley floors as terraces in which remnants of the river flood plain placers are preserved. In old age the level of the whole land is reduced to a peneplain characterized by a low relief with low rounded hills, shallow valleys, rolling landscapes and sluggish meandering rivers, marked by oxbow lakes that flow in various directions following the very low gradients that prevail. Few if any placers are formed during this stage.

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[28] In heavy mineral studies, mineral grains deposited at the same time are considered as hydraulically equivalent or equi-settling, under the conditions prevailing during deposition. Various factors, principally specific gravity and grain shape, are of importance in determining the relative size of hydraulically equivalent grains. The theoretical and practical aspects of the hydraulic equivalence of grains, with a bibliography, are discussed by McIntyre (J. Geol., v. 67, p. 278–301, 1959).

In arid climates the evolutionary pattern is significantly different, mainly because of reduced rainfall, the absence of thick soil cover and the lack of vegetation. Wind erosion is more important in such climates; extensive downhill creep along valley sides is reduced because of the lack of moisture, and numerous basins of interior drainage develop generally with no connections to oceans. The infrequent precipitation during the youthful stage gives rise to numerous nonintegrated streams in steep-walled valleys that cut deeply back into the highlands. With increasing maturity a poorly integrated drainage develops mostly into closed basins that are marked by pediments on which alluvial fans may form. In old age the drainage pattern is generally completely disintegrated, there being in most districts no streams of any length and commonly no interconnection between those that do exist during a pluvial period. Arid conditions are not particularly favourable for the formation of placers, although some may form in gulches, in canyons and in alluvial fans on pediments where the conditions are right. Arid areas are, however, often characterized by great spates and walls of water that come off the highlands or mountains during cloud bursts, rush down the dry washes, gulches, canyons and valleys carrying everything before them, and finally debouch onto the alluvial fans on pediments or into the closed basins. Such violent activity is not conducive to the formation of placers; on the contrary any that formed would be sluiced down the gulches, creeks and canyons and the gold spread indiscriminately over the lower valley bottoms and inland basins.

Desert placers as a whole are small and the pay streaks are often erratic and commonly scattered. 'Bajada' or 'pediment placers' in desert terrains may be more productive, but they are commonly difficult to work. Descriptions of some typical desert placer areas in the southwestern United States and Mexico may be found in the publications by Haley (1923), Webber (1935), Vanderburg (1936), Wilson and Fansett (1961) and Johnson (1972*a,b,* 1973*a,b,* 1974).

The above descriptions characterize the normal evolution of drainage patterns and the formation of placers under the extremes of humid and arid conditions. But many abnormal conditions prevail in any particular district. Sudden uplifts at the mature or old age stages cause renewed downcutting of channels and destruction or deep burial of placers already formed. Similarly, great or sudden increases in rainfall may produce floods that sluice out the gulches, creeks and canyons, change the courses of the rivers, and greatly modify, destroy or bury the most recent placers. Depressions of valleys may result in basins in which lakes develop or inlets are formed, which are invaded by the ocean. These ultimately become filled with sediment burying deeply any placers formed in the valleys. Finally, glaciers forming in high mountains and extending down gulches and valleys may plough out all sediments and scatter the placer materials far and wide.

The location of the pay streaks in placers is of prime interest to the placer miner. Given an adequate primary gold source pay streaks in general are fairly uniform and have considerable continuity in moderately hilly country where uniform rainfall has prevailed and where deep secular decay has been followed by a gradual restricted uplift. Any aberrations in this ideal pattern invariably cause marked variations in the tenor and continuity of the pay streaks. The richest pay streaks are those produced by reworking of preexisting auriferous gravels.

The law of the pay streak in placer deposits is variable depending on whether the placer is formed in gulches, in river channels, on flood plains or in deltaic deposits. Lindgren (1911, p. 66) said of the pay streak referring to the deposits of the Sierra Nevada of California, some of which are buried beneath Tertiary lava flows:

> It has become almost an axiom among miners that the gold is concentrated on the bedrock and all efforts in placer mining are generally directed toward finding the bedrock in order to pursue mining operations there. It is well known to all drift miners, however, that the gold is not equally distributed on the bedrock in the channels. The richest part forms a streak of irregular width referred to in the English colonies as the "run of gold" and in the United States as the "pay streak" or "pay lead". This does not always occupy the deepest depression in the channel and sometimes winds irregularly from one side to the other. It often happens that the values rapidly diminish at the outside of the pay lead, but again the transition to poorer gravel may be gradual. An exact explanation of the eccentricities of the pay lead may be very difficult to furnish. Its course depends evidently on the prevailing conditions as to velocity of current and quantity of material at the time of concentration.

Tyrrell (1912) while admitting the fickle nature of the pay streak concluded that "the pay-streak is a feature in the structure and growth of the valley in which it occurs, its formation is governed by certain geological laws, and those laws should be recognizable without great difficulty if the growth of the valley can be traced with reasonable accuracy."

The features of the evolution of valleys is discussed above, but this knowledge is only of general value in studying placers. To accurately determine the location of their pay streaks, especially in the buried types and those on flood plains and deltas, requires detailed profiling by trenching or overburden drilling. Geophysical methods may assist in some terranes. Where the cover is light and the bedrock magnetically low, a magnetometer survey may outline the position of the magnetic 'black sands' so commonly accumulated with gold. Where the bedrock has a higher magnetic intensity than the gravel, the position of magnetic lows may indicate the position of the pay streak channels. Electrical methods may also assist where there are conductivity or other differences between the bedrock and the basal alluvium. Hammer seismic methods under favourable conditions can also be used for profiling and outlining the notches or gutters containing pay streaks. The pay streak in gulches and youthful streams is generally easily located. It is commonly in or near the notch or gutter of the V-shaped valley or gulch on and just above bedrock (Fig. 71).

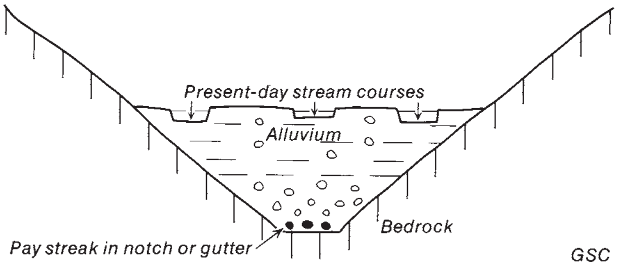

Figure 71. Sketch showing the location of an auriferous pay streak in the notch or gutter of a V-shaped valley or gulch.

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As the valleys mature, widen out and become filled with sediments the streams shift their location from time to time, and the pay streaks may no longer be in the lowest depression or gutter. Furthermore, pay streaks long since buried may bear no relation to the present streams (Fig. 72). Pay streaks in wide valleys, flood plains and deltas are extremely irregular in their distribution and are the product of an environment where shifting channels and migrating meanders hold sway (Fig. 73). In most streams and rivers where placers are forming, gold collects along bars due to some obstruction, diversion or slackening of the water course in the slower moving water on the inside curves of fast-flowing meanders, in the main stream near the mouths of tributaries and elsewhere where slack water prevails (Fig. 74). These guides are useful in the study of both recent and ancient water courses. With respect to the latter, however, care must be taken to ascertain the direction of the paleogradients. For instance the Tertiary channels of the Sierra Nevada have been tilted by movements initiated by block faulting so that some of the gold channels now 'run up hill' as compared with the present gradient of the country.

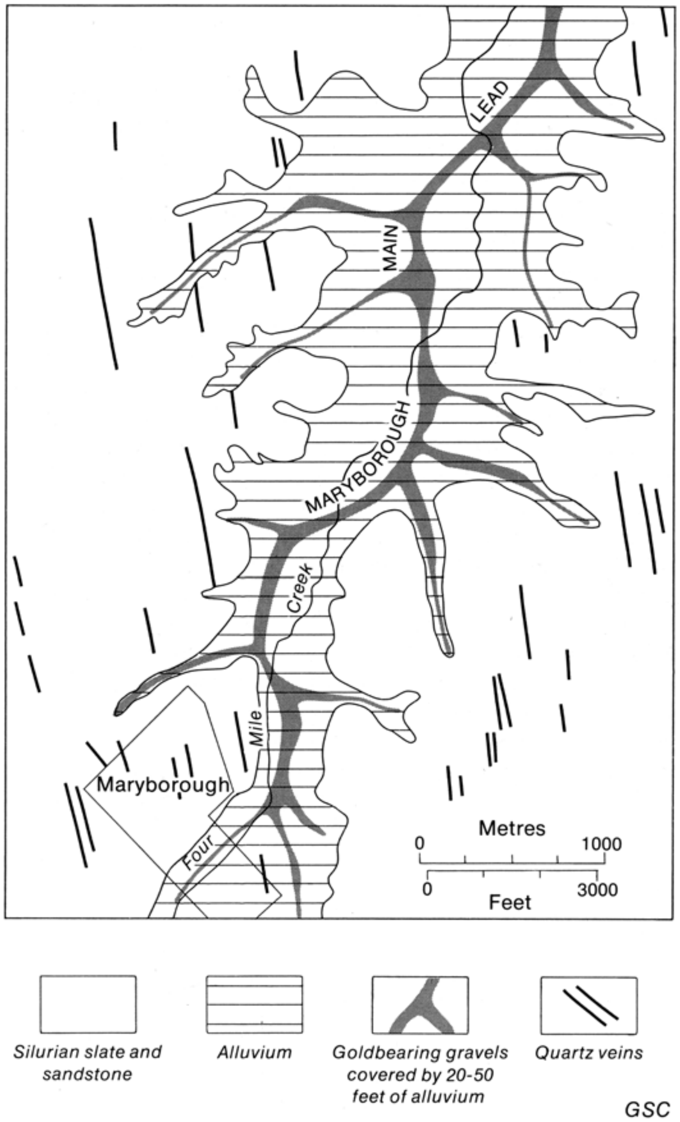

Figure 72. Generalized map showing the position of the pay streak in the auriferous gravels in relation to the present stream system, Maryborough, Victoria, Australia (after Hunter, 1909).

Pay streaks may be reworked by subsequent streams in the same or different courses into exceedingly rich concentrations (Fig. 75). In a broader areal sense the reworking of former placers may also be economically important in places. Thus, the lean placer concentrations of gold and platinum formed during the Mesozoic and early Tertiary in the Urals, U.S.S.R. were uplifted and crossed by a Pliocene-Quaternary drainage system in which rich new placers were concentrated (Sigov *et al.*, 1972).

Deltas may form in rivers, lakes, seas and oceans, but few gold placers in deltas in these locations have been described, probably because they are relatively rare. The principles governing the pay streaks in deltas are the least understood. Deltas in rivers tend to concentrate gold in fairly well-defined streaks just downstream from the mouths of the streams, mainly in topset and foreset beds if these are developed. Deltas in lakes commonly receive only fine-grained to very fine-grained (flour) gold, and the metal may be dispersed more or less throughout the sedimentary pile. In some cases, however, the fine-grained gold may collect in streaks on the foreset beds, and these may have relatively high angles of inclination. Deltas in seas and oceans do not seem to develop well-defined streaks, probably because of the extremely fine subdivision of most of the gold reaching the oceanic environment. If streaks do develop, they are usually erratic and seem to be mainly located in the topset and foreset beds.

An unusual type of (alluvial) placer is described by Bensusan (1942) in Burma. This placer, near Tenasserim, consists of gold in mangrove swamp mud. The gold appears to be present in a colloidal form since repeated examinations of samples and concentrates under a high power microscope failed to show any free gold. From the description it would seem that this is a case of concentration of gold in a humic environment, perhaps by chelation or other organic bonding (*see* also Chapter II). The swamp mud averages about 0.285 ppm Au and is said to contain some £200 million worth of the metal.

At this point a few words should be said about alluvial placers originating from the reworking of glacial debris by glacial and later streams. Some examples of these are given later in the descriptions that follow, and hence only generalities need concern us here.

Valley glaciers give rise to vast terminal moraines and during wasting may clog the valleys with great accumulations of glacial till, clay and sand. If these glaciers have scoured valleys containing gold placers or the sides of valleys containing oxidized or unoxidized gold deposits, the glacial materials may be slightly auriferous. Reworking of these materials by meltwaters and subsequent streams may produce stream and river placers in the normal manner. Many of these placers are often buried, difficult to recognize, and their pay streaks are frequently erratic. Nevertheless, a number of these types of placers have been worked in the past particularly in New Zealand (Park, 1969; Williams, 1974), and there are others in the Rocky Mountains of Canada and the United States, and elsewhere.

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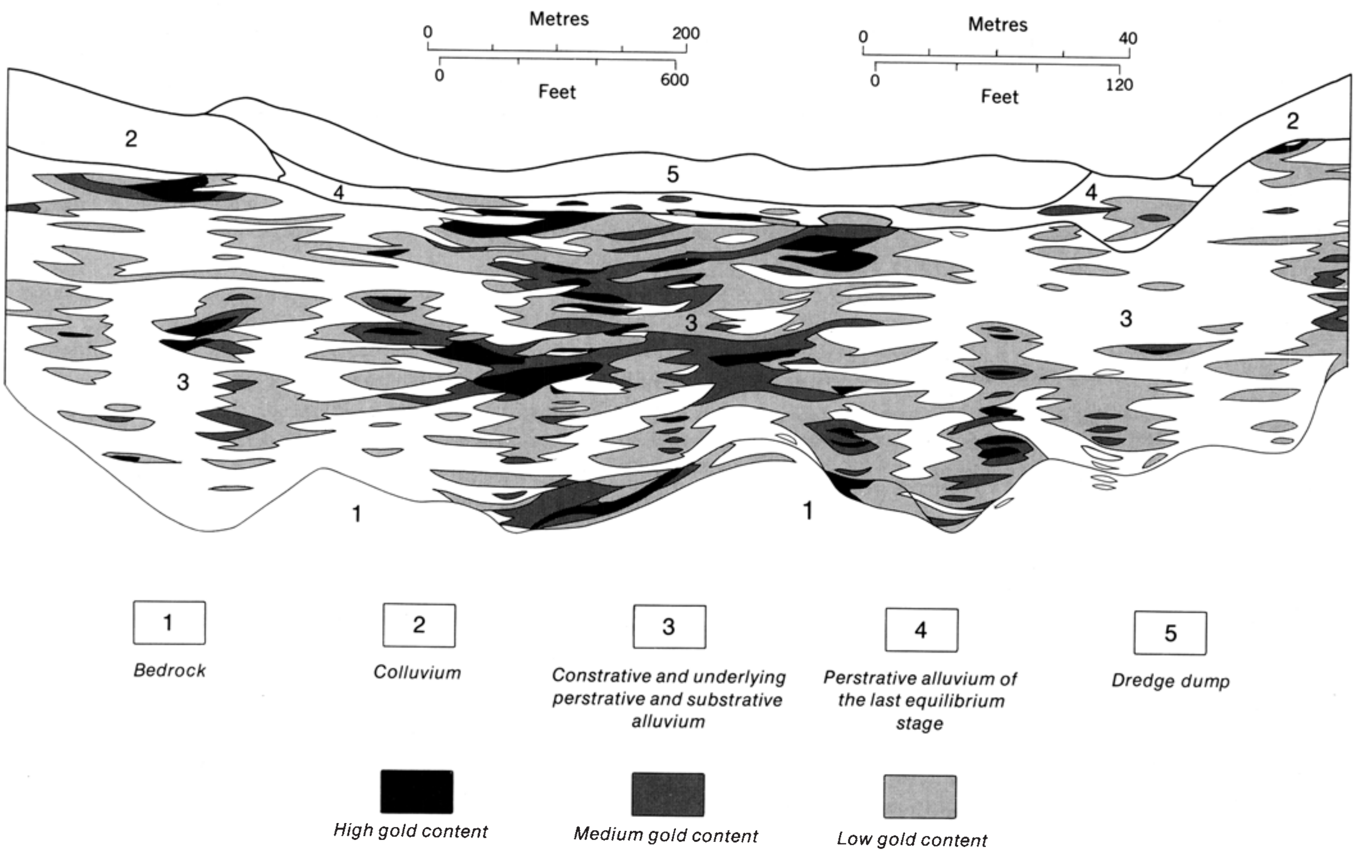

Figure 73. Cross-section of an allochthonous gold placer in the valley of the Kuranakh River, southern Yakutia, U.S.S.R. (after Kartashov, 1971).

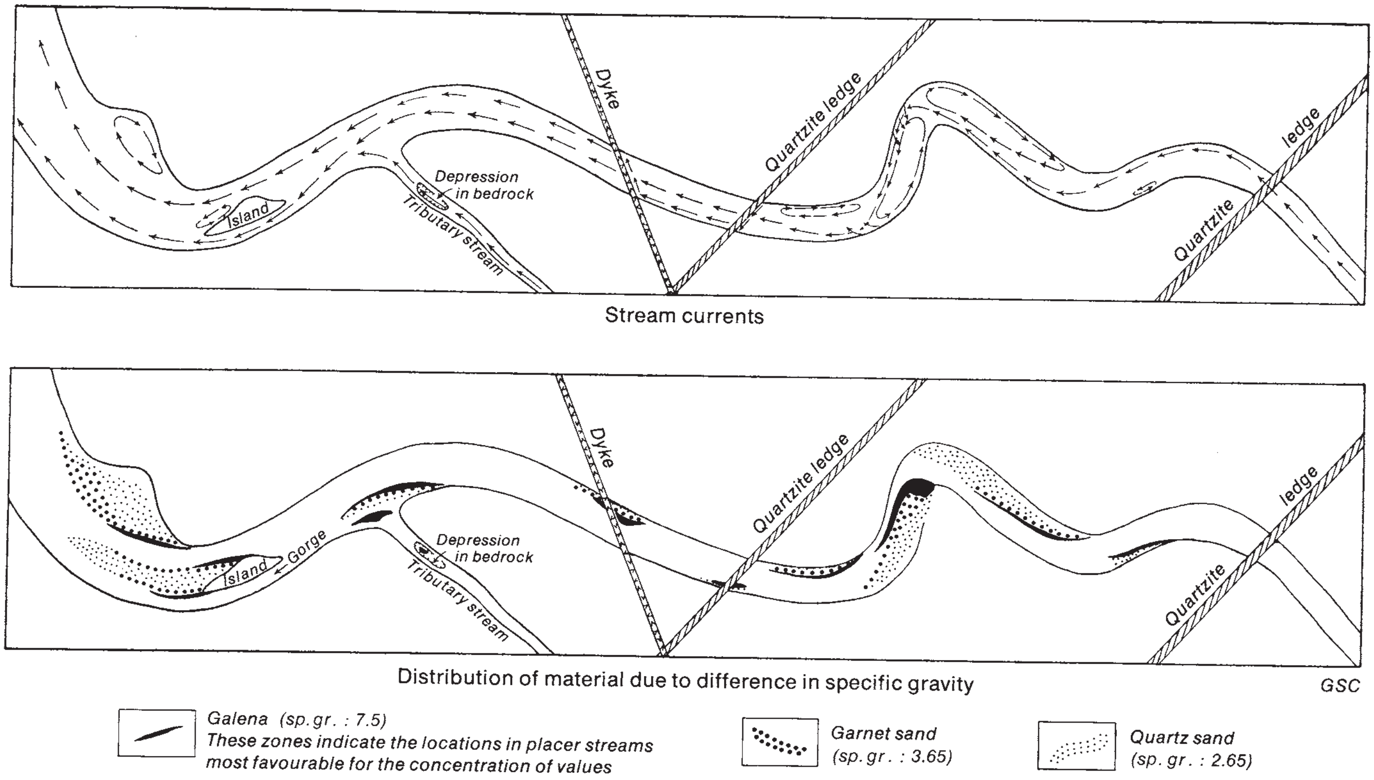

Figure 74. Diagram of a laboratory stream showing currents and distribution of sedimentary materials of different specific gravity (after MacKay, 1921). Galena was employed as the mineral of high specific gravity. The analogy with the placer conditions found in most rivers and streams with moderate gradient is excellent.

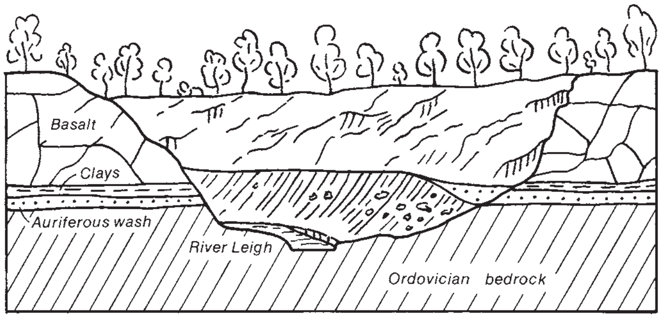

Figure 75. Sketch showing reworking by subsequent stream of an older pay streak, River Leigh, Victoria, Australia (after Hunter, 1909). An old auriferous sub-basaltic river is crossed by the present stream in which some payable gold was found downstream from the old pay streak.

The action of piedmont glaciers and ice sheets (continental glaciers) has generally been disruptive and destructive of preexisting placers. In places, however, there have been reconcentrations by glacial streams from the disrupted placers as in Yukon, British Columbia, Quebec, Siberia and elsewhere. Some of these are described subsequently.

From the general considerations discussed above, and others that will be mentioned subsequently in the text, some general conclusions about the concentration of gold and other heavy minerals in alluvial placers can be stated.

1. Coarser gold is generally deposited in the upper reaches of a placer gulch, stream or river, and the finer grained gold is generally deposited in the lower reaches of placer water courses.
2. The richest and coarsest gold and nuggets are commonly deposited in the layers with comparatively coarse sediment, and the finer gold particles are commonly deposited in the finer, sandy fractions of the sediment.
3. Gold should normally occur in streaks with other heavy minerals such as magnetite, scheelite, barite, etc.
4. Gold found on a bottom with a steep gradient will commonly be coarser than that found on a flat-lying level bottom.
5. In narrow gulches and gorges mainly coarse gold will be deposited.
6. Little gold will lodge in places where scouring action is marked.
7. Pot holes do not generally form effective lodgements for gold mainly because of the centrifugal grinding action and ejection of fine gold from such sites.
8. On a favourable bottom the gold generally collects on the downstream side of natural riffles.
9. Zones of slack water in water courses are favourable sites for the accumulation of gold particles.
10. Glaciation does not preclude the occurrence of placers.

Beach placers

Beach placers can be subdivided into two categories – modern and fossil. They are formed by the winnowing action of waves, undertow and alongshore currents along present and past shorelines bordering lakes, seas and oceans where a source of primary gold has been available for concentration. Tidal movements and strong winds may accentuate the concentrating processes in some places. Beach placers tend to form predominantly along rectilinear shorelines; few are known along markedly broken and rocky shores. The source of the gold may be in the rocks along the shores; in sediments deposited by streams upon the coast; and in slightly auriferous stream or river terraces, sea terraces and gravel plains that border the coasts.

The constituents of beach placers are essentially the same as those in the alluvial category. Quartz pebbles and sand predominate, but on some beaches there may be considerable shingle composed of the pebbles and stones of the country rock of the adjacent region. Magnetite and ilmenite form the bulk of the heavy minerals in most deposits. Clay beds and hard pans are common in some beach deposits especially in those of a raised character. These may form false bottoms for pay streaks. Coquina accumulations may be present in some instances and may mark the lines along which the richest pay streaks occur in modern beach placers. In fossil beach placers coquina may be invaluable as marker horizons.

Most of the gold in beach placers is fine grained and generally of high fineness, commonly greater than 900. The richest pay streaks usually follow the strand lines; most are a few inches to a few feet in thickness and generally only a few tens to several hundred feet in width (Figs. 88 and 89). Their continuity along the strandline is frequently erratic, and numerous cutouts are encountered. Elevation or depression of the land leads respectively to the formation of raised or deeply buried beach placers.

Descriptions of typical auriferous alluvial and beach placers and districts

Alluvial placers were the first type of gold deposits worked by man. Ancient Chinese and Hindu writings mention these deposits, and we have the story in Greek mythology of Jason, commander of the good ship *Argo*, who sought the Golden Fleece at Colchis in Asia Minor on the far shore of the Euxine (Black) Sea (Frontispiece). The metal gold also figures extensively in the Old Testament, and there are many allusions to its source in placers. Herodotus and Strabo, the Greek historian and geographer respectively, repeatedly mention the working of alluvial placers in Thrace, the Aegean Islands and Asia Minor. Pliny, writing at the beginning of our era, describes many of the Roman placer operations, which seem to have stretched from Asia Minor to Spain, France and Wales. In particular he mentions gold in the stream beds of the Tagus in Spain, the Po in Italy, the Hebrus in Thracia, the Pactolus in Asia Minor and the Ganges in India, the last probably from heresay. Pliny mentions booming and sluicing and collection of gold on ulex, a rough, prickly plant that was burned and the gold washed out of the ashes. In the Dark and Middle Ages some gold was won from the old placers of the Mediterranean area and western Europe, but by the time of the rediscovery of America by Columbus in 1492 nearly all of these placers were exhausted.

When Columbus made his first landfall in the New World he found the natives in possession of gold, and later exploring in Hispaniola (Haiti) in 1493 on the second voyage he observed crude placer operations in the streams and rivers of the interior. In 1494 Alonso de Ojeda discovered the rich

Cibao placers, and a year later Pablo Belvis arrived from Spain with a large quantity of mercury for amalgamation purposes. The first gold won was sent immediately to the King of Spain, who donated it to Pope Alexander VI in Rome where it was dedicated to the service of Christianity in the gilding of a cathedral dome. Thus began the *auri sacra fames* of the Spaniards in America that was to wreak such havoc on the natives and was also to introduce the Negro slave trade to the New World. The sordid story has been told many times and need not be repeated here; it is one of the black pages in the history of gold mining.

A more pleasant story can be written about the great gold rushes of the last century. Alluvial gold gravels were worked in the Altai of Siberia as early as 1820, but some 9 years later extensive alluvial deposits were found in the Lena Basin, probably the largest alluvial gold deposits known. These discoveries led ultimately to the colonization of southern Siberia. These and other deposits in eastern Siberia are still worked extensively today. The great gold rush of 1849 to California can be said to have opened up the American west. The California gold rush was followed in 1851 by the Australian rushes to New South Wales and Victoria, an impetus to mining that has kept Australia in the forefront of world mineral production ever since. The golden gravels of the Fraser River in British Columbia were known as far back as 1852, but it was not until 1858 that the great stampede up the Fraser began ultimately in 1861 reaching Williams and Lightning creeks in the Cariboo, the most celebrated of all gold creeks in the province. Gold placers in the Yukon Basin were worked as early as 1880, but it was not until 1896, and perhaps 2 years earlier according to some accounts, that gold was discovered on the tributaries of the Klondike River. The great rush took place in 1897–1898 to Dawson – one of the greatest gold rushes in history and certainly the most colourful, made immortal by Robert W. Service in his novel *The Trail of '98*, and in his poems, *Songs of a Sourdough* and *Ballads of a Cheechako.*

Alluvial gold placers in streams and rivers have been the richest and of most interest to the prospector. But some beach placers have also caught his eye and have been extensively worked. Gold was discovered in Alaska as far back as 1865–1866 and alluvial prospecting in the streams and rivers near Nome was in full swing in 1899, the year that gold was discovered on the beaches by a soldier and a prospector. There followed a frenzied digging and grubbing along the coast for many miles, more than one million dollars having been won by hand rockers in less than 2 months (Collier *et al.*, 1908).

The methods of the alluvial placer miner have changed much since Jason's time. Originally, early man probably plucked by hand the heavy shining nuggets from the gravels of the streams. This is the stage at which Columbus and his mining engineers found some of the natives working the placers of Haiti. Later the gravels of the streams were stirred up by the workers using crude booming (hushing) operations and sluiced over the fleeces of sheep and goat pelts, the gold remaining mainly trapped within the wool and goat's hair. This method is apparently still employed in some of the placer streams of Asia Minor, Afghanistan and Mongolia. Panning is an old technique certainly known to the ancients of the Old World and the natives of Africa, who used the calabash (gourd) and the natives of Central and South America who employed the batea. The rocker and the sluice were known to the Greeks and Romans, and they were adept at booming (hushing) operations. The dry washer or dry blower has long been known to those who have sought gold under desert conditions. The water monitor-, bulldozer- and dragline-sluice operations and the great mechanical dredges are modern mechanical adaptations of age-old techniques of separating the gold from the dross.

Gulch and creek placers

Gulch and creek placers are common in nearly all placer districts of the world. They lie in the small valleys, guts and gulches that are tributary to the main stream systems of a district. Literally thousands of these deposits have been worked, nearly all in a small way. The main characteristics of these types of placers are:

1. Most occur in moderately hilly country exhibiting the effects of protracted weathering and denudation. A few occur in regions of alpine topography, but these are generally marked by spotty pay streaks.
2. The gradients of the present (and past) stream systems are moderate.
3. The source of the gold and associated heavy minerals is generally close at hand, either at the heads of the gulches and creeks or along their valley sides. The source of the gold is commonly auriferous quartz veins or gold-bearing sulphide bodies; disseminated gold in quartz blows and stringers in the country rocks and in pyrite and other sulphides in graphitic shales and other rocks is the principal source in some instances.
4. The heavy mineral constituents accompanying the gold are mainly those found in the primary gold deposits, in closely associated deposits or in the enclosing country rocks.
5. The gold is usually coarse and commonly higher in fineness than that in the primary deposits. Large nuggets, wires and crystals are a feature, and nodules of vein quartz or sulphides with veinlets of gold or containing disseminated gold are common.
6. The pay streaks are rich and generally on the bedrock or in the top few feet of the bedrock. Most pay streaks are well defined and fairly regular. False bottoms may occur but are not a common feature.
7. The overburden covering the pay streaks is generally not deep except in depressed areas or where glacial deposits complicate the picture.

Gulch and creek placers are common in the Yukon and a number occur in the Keno Hill–Galena Hill area. One in particular, Dublin Gulch, is typical and will serve as an example of what one might expect to encounter with gulch and creek placers the world over.

The Dublin Gulch and Haggart Creek placers (Fig. 69), discovered and first worked in 1898, have been described in some detail by Keele (1905), Bostock *in* Little (1959), Boyle (1965*a*) and Boyle and Gleeson (1972). The topography is characterized by relatively low rounded hills and numerous small streams tributary to the main water courses, all marks of a deeply dissected upland. The bedrock of the area is folded and faulted quartzite, phyllite, graphitic schist, limestone and quartz-mica schist of the Yukon Group intruded by a body of granodiorite and granite probably of Cretaceous age. Skarn, carrying scheelite, is developed in places near the granitic rocks. In addition there are numerous quartz stringers carrying wolframite and scheelite in the granitic rocks and their contact zone, a cassiterite-tourmaline lode and several northeast striking gold-bearing quartz-arsenopyrite-pyrite-sulphosalt veins. Primary vein material in these veins averages about 0.2 oz Au/ton and 1.5 oz Ag/ton. The gold is largely submicroscopic to microscopic and is mainly in the arsenopyrite, pyrite and sulphosalts; only rarely is free gold seen in the quartz and sulphides.

The country rocks and the gold-bearing veins are deeply weathered, the latter down to at least 20 ft. The stable minerals in the oxidized zones of the veins are mainly scorodite, limonite, residuals of pyrite and arsenopyrite and some anglesite and beudantite. Assays of the oxidized material are highly variable in gold content, ranging from 0.015 to 0.30 oz Au/ton; the silver content is, likewise, highly variable averaging about 0.5 oz/ton. The gold in the oxidized zones consists of fine dust, small flakes and abundant wires. Some of the gold is closely associated with the scorodite and limonite and is probably in a chemically bound or adsorbed form. Most of the gold in the oxidized zones is about 850 fine, although there are marked differences from vein to vein.

The area immediately around Dublin Gulch is beyond the limit of the last well-marked Pleistocene glaciation, but evidence of an early glacial incursion is present as witnessed by what seem to be remnants of weathered tills and also by the appearance in the placer concentrates of nodules of hematite (iron-formation), which probably came from the Snake River deposit in northern Mackenzie Mountains, Yukon. The streams in Dublin Gulch and Haggart Creek have entrenched parts of their courses in deep overburden forming terraces with old modified profiles. The exact nature of the original profile in the lower part of Dublin Gulch is difficult to ascertain because of the extensive stirring and digging since 1898. What appears to have been present at the surface was about 6 to 8 ft of gravels, schist particles, soil and granite boulders, probably mainly due to creep and slope wash. This was succeeded in places by 2 to 3 ft of bluish clay that overlay 3 to 4 ft of yellowish (limonite coated) gravels and weathered debris. The last materials represent the detritus arising from deep secular weathering of the bedrock of the area and the contained deposits during a period of uplift in late Tertiary time.

According to old reports fine colours of gold occurred in the surface materials where washed by the stream in the gulch. Most of the gold, however, is on the bedrock in the bottom foot or so of the lower gravels and weathered debris. The pay streak begins at Bawn Bay Gulch and continues with only a few breaks downstream. It is about 100 ft wide near the mouth of Dublin Gulch, narrowing gradually upstream. The grade is about 0.03 oz/yd.

The gold is accompanied by scheelite (about 1 lb/yd^3), some wolframite and a little cassiterite. In addition there are a number of other heavy minerals, including magnetite, hematite nodules (iron-formation), arsenopyrite nodules, jamesonite nodules, bismuth, galenobismutite, rarely bismuth tellurides, pyrite, tourmaline and garnet. The gold is present as fine dust, scales, rough wires and sprigs, occasional crystals and small nuggets ranging from pea size up to about the size of hickory nuts. Most of the nuggets are worn and pitted. The writer did not observe any free gold in the quartz or sulphide pebbles and so far as is known none of this type of gold has been reported. Mustart (1965), however, found angular arsenopyrite fragments in some of the nuggets. The principal minor and trace metals in the gold are Ag, Cu, Fe, Hg, Bi and Sn. All of these occur in the deposits from which the gold came. The average fineness of the Dublin Gulch gold is about 900.

The Dublin Gulch area provides an excellent example where gold can be traced from primary deposit to stream placer. The primary gold is mainly microscopic to submicroscopic and associated with pyrite, arsenopyrite and sulphosalts. Particles of gold greater than 100 μ are rare in the writer's experience. On the oxidation of the sulphides and sulphosalts the gold was released and formed flour or mustard gold in some cases, but there was also a nucleation and growth of gold on fine rough wires, flake and small nuggets in the oxidized zones. All of these types of gold passed gradually into the eluvium where they probably accreted more gold on their journey to the gulch. Here, they passed slowly down gradient, some particles possibly accreting more gold but most being rolled along and hammered by the pebbles of the mills of nature. The fineness has changed during the journey from oxidized zone to placers in Haggart Creek a distance of some 3 mi. In the oxidized zones the fineness averages about 890; in Dublin Gulch 900 and in Haggart Creek 925.

Stream and river placers

The main features of these placers are discussed in some detail above. Briefly their characteristics are: (1) most occur in districts with a subdued topography marked by broad, often terraced, entrenched valleys developed in a terrain of rounded, deeply weathered hills; (2) the present (and past) gradients of the streams are moderate to low; (3) the pay streaks are generally not as rich as those in gulches and creeks, but they are longer, commonly wider and more uniform. Multiple pay streaks may occur at the same elevation or they may be stacked at different elevations. Most of the rich pay streaks are on the bedrock; (4) the gold is generally finer grained than that in creek and gulch gravels. Large nuggets are relatively rare in stream and river placers; (5) the fineness of the gold is usually higher than that in creek, gulch and eluvial placers; (6) the overburden is commonly tens of feet to hundreds of feet deep; and (7) most stream and river placers are amenable to large scale hydraulicking and dredging operations.

There are many famous districts where stream and river placers have been extensively worked. Some provide good examples and will be described briefly. They include the Klondike district in Yukon, the Cariboo and other districts in British Columbia, the Chaudière and other areas in southeastern Quebec, the Sierra Nevada of California; the Chocó in Columbia, the deep leads of Victoria, Australia, and the extensive placers of the Lena, Aldan, Amur and other drainage systems in Siberia, U.S.S.R., Mongolia and northern China.

Klondike district, Yukon. The stream and river placers of the Klondike district near Dawson, Yukon were discovered in 1896 or earlier and have yielded some 10 million ounces, more

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than half of the placer gold production of the Western Cordillera of Canada. Their heyday is past, although there are still some small hydraulic and bulldozer operations on some of the streams. Extensive descriptions of the placers of the Klondike are given by McConnell (1905, 1907) and more recently by Gleeson (1970).

The most productive creeks were Bonanza, Hunker, Dominion, Gold Run, Sulphur and Quartz (Fig. 76). The underlying bedrock is mainly the Klondike Schist (Klondike Series) comprising folded and faulted sedimentary quartz-mica schists, chlorite schists, sericite schists, quartzites, phyllites, pyritic graphitic schist and highly sheared quartz porphyry sills or flows sandwiched between the sediments. The age of these rocks is not precisely known; they are probably Precambrian.

Throughout the Klondike Schist there are myriad primary quartz bodies, most carrying traces to small amounts of gold. Briefly these bodies include:

1. Quartz boudins, blows, stringers and bedded veins sandwiched between the sedimentary beds: These carry small amounts of pyrite and all are auriferous carrying however, only small amounts of gold, generally in the range of 0.01 to 0.05 oz/ton.

2. Quartz-barite veins containing minor amounts of galena: Most of these veins are slightly auriferous containing approximately 0.02 oz Au/ton and 0.03 oz Ag/ton. The gold is said to occur in the native state in these deposits.

3. Quartz veins in the chloritic phase of the Klondike Schist: Some of these veins and their adjacent wall rocks contain coarse cubes of pyrite and minor amounts of galena. Spectacular specimens of free gold are said to have been obtained from these veins. On the average, however, the quartz and pyrite are only feebly auriferous.

4. Stringers, veins and irregular lenses of quartz in extensive, wide northwest-trending shear zones that exhibit marked sericitization and pyritization: The metallic minerals are mainly pyrite, galena and sphalerite. Some barite is present. Gold values are spotty and appear to be concentrated in pockets with galena, sphalerite and pyrite. Some of these assay in the ounces per ton; the quartz zones as a whole are very low grade (0.01–0.05 oz Au/ton). The gold is mainly free as small grains and ragged particles.

The pyritic graphitic schists of the Klondike Schist are also feebly auriferous. They contain about 0.005 ppm Au, mostly in the pyrite, samples of which contain up to 2 ppm Au according to our analyses.

The Klondike district is a thoroughly dissected upland, a part of the Yukon Plateau, marked by rounded hills and a multitude of small streams tributary to the main water courses. The valleys are flat and wide in their lower reaches, but gradually narrow towards their heads into steep-sided narrow gulches ending abruptly in broad amphitheatres. Many of the lower slopes of the valleys are conspicuously terraced. The district has not been glaciated, but is underlain by permafrost, in places to a depth of 200 ft. This necessitates thawing the ground out before dredging operations can begin.

The placers of the Klondike owe their existence to a general uplift in late Tertiary time followed by deep secular weathering of the bedrock and the contained gold-bearing quartz bodies. V-shaped valleys were formed first, and these were gradually widened and filled at maturity with extensive gravel deposits. A later period of uplift, probably of Recent or Late Pleistocene age, has resulted in the streams channelling their valleys deeply, almost to bedrock in places, and leaving the characteristic terraces as benchmarks in their downward migration.

McConnell (1905) classified the auriferous Klondike gravels into three categories as follows:

- High level gravels
  - River gravels
  - White Channel gravels
    - Yellow gravels
    - White gravels
- Gravels at intermediate levels
  - Terrace gravels
- Low level gravels
  - Gulch gravels
  - Creek gravels
  - River and stream gravels

Their stratigraphic relationships are shown in Figure 77, and their description as given below is paraphrased only slightly from McConnell's classic report.

The 'low level creek gravels' are the most important gravels in the Klondike. These gravels floor the bottoms of all the valleys to a depth of from 4 to 10 ft. They rest on bedrock usually consisting of decomposed and broken schists and are overlaid by a sheet of black frozen muck ranging in thickness from 2 to 30 ft or more. They are local in origin and consist entirely of the schists and other rocks outcropping along the valleys. The schist pebbles are usually flat round-edged discs measuring 1 to 2 in. in thickness and 2 to 6 in. in length. They constitute the greater part of the deposit but are associated with a varying proportion of rounded and subangular quartz pebbles and boulders, and less frequently, with pebbles derived from the later eruptive rocks of the region. The pebbles are loosely stratified, are usually embedded in a matrix of coarse reddish sand and alternate in places with thin beds of sand and muck.

The creek gravels frequently enclose leaves, roots and other vegetable remains and also the bones of various extinct and still existing northern animals, such as the mammoth, buffalo, bear, musk-ox and mountain sheep and goat.

The 'low level gulch gravels' occupy the upper portions of the main creek valleys and small tributary valleys. They differ from the creek gravels in being coarser and more angular. A considerable proportion of their material consists of almost unworn fragments of schist washed down from the adjacent slopes. They contain the same vegetable and animal remains as the creek gravels.

The only 'low level river gravels' of the district proven, so far, to contain gold in paying quantities occur in the wide flats bordering the lower portion of the Klondike River below the mouth of Hunker Valley. The river gravels consist of quartzite, slate, chert, granite and diabase pebbles largely derived from the western slopes of the Ogilvie Range. They are harder and better rounded than the creek gravels, a result of the greater distance travelled.

The 'intermediate level terrace gravels' lie on rock terraces that occur at various points cut into the steep slopes of the present valleys. The terraces were produced during the

Contents

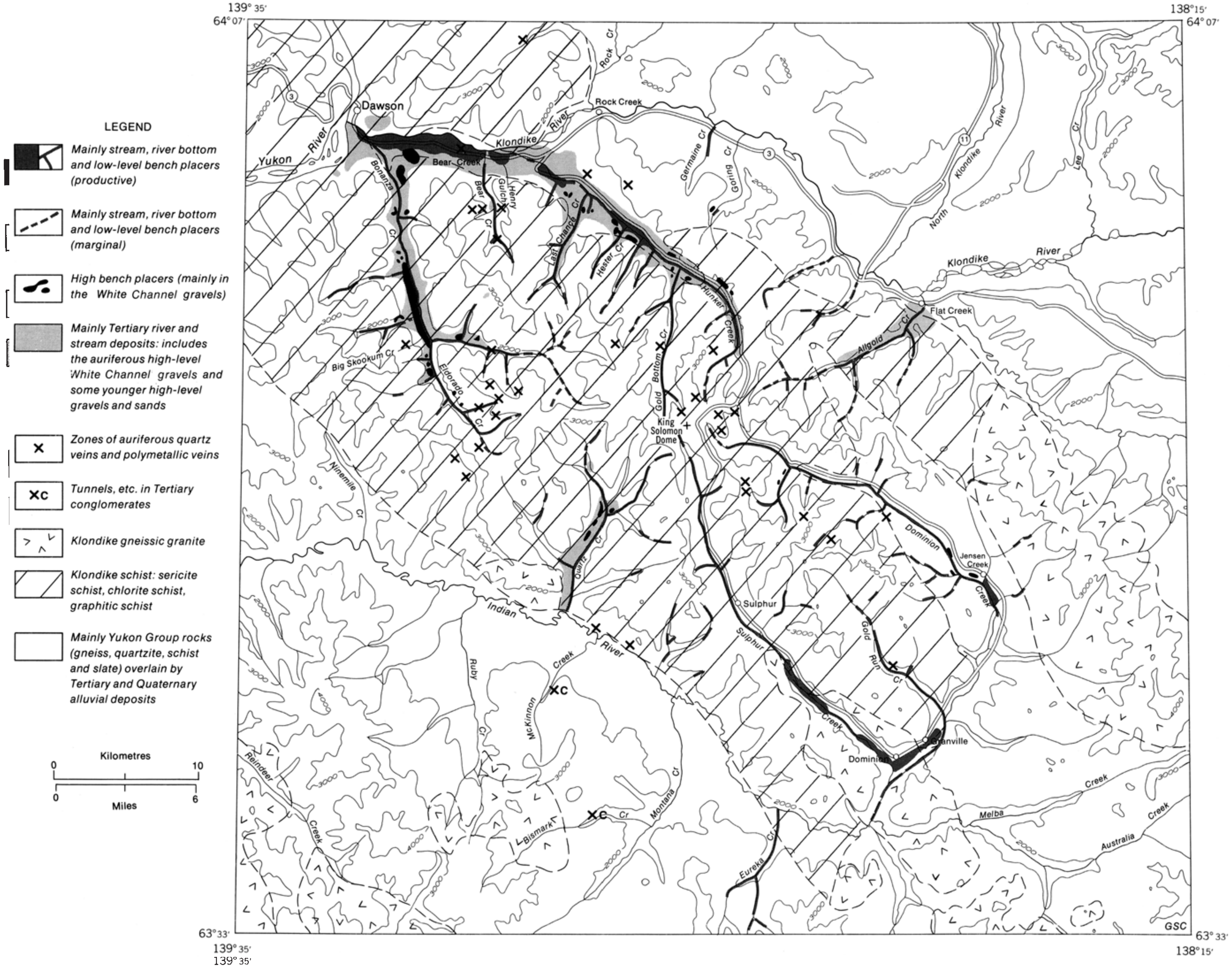
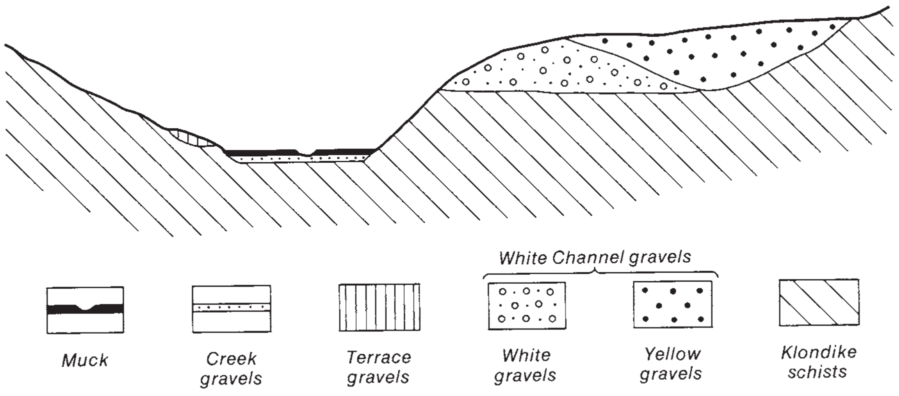
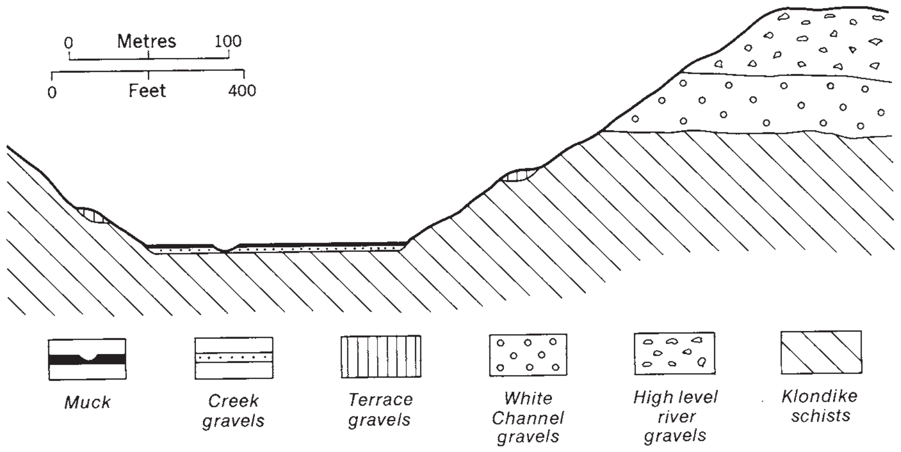


Figure 76. Generalized geology of the Klondike (Dawson) district, Yukon showing the relationship of the gold placers to the Klondike schist and other rock units (after McConnell, 1905, 1907; Bostock, 1942; Gleeson, 1970; Green and Roddick, 1972; with additions by the writer from field observations and airphotos).



Section across Bonanza Creek valley below Eldorado Forks



Section across the lower part of Bonanza Creek valley

GSC

Figure 77 Generalized sections across the placer deposits of Bonanza Creek, Klondike (Dawson) district, Yukon (after McConnell, 1907).

deepening of the valleys and are simply remnants of former valley-bottoms. Most are small, seldom exceeding a few yards in width and a few hundred yards in length, irregular in distribution and occur at all elevations up to the bottoms of the old valleys. The beds of gravel supported by the terraces are usually from 6 to 15 ft in thickness, very similar to those in the creek bottoms but showing somewhat more wear. The terrace gravels, like the creek gravels, are overlain, as a rule, with muck, and at one point on Hunker Creek were found buried beneath 100 ft of this material.

'High level river gravels' are extensively distributed along Bonanza and Hunker creeks and some of their tributaries and also occur on Eldorado, Bear, Quartz, Nine Mile and Allgold creeks. They consist, principally, of ancient creek deposits overlain near the mouths of some of the valleys by gravels laid down by the Klondike River when it ran at a much higher level than at present and occupied a somewhat wider valley.

These gravels occur at various points along the Klondike River. In the Klondike district they are found covering the small plateaux in which the ridges separating Bonanza and Hunker creeks from the Klondike River terminate. They rest, in both places, on high level creek gravels at an elevation of about 450 ft above the present valley bottoms. They have a thickness of from 150 to 175 ft, and consist principally of well-rolled pebbles of quartzite, slate, chert, granite, diabase and conglomerate embedded in a matrix of grey sand and derived, like those in the present stream, from the western part of the Ogilvie Range. The high level river gravels are reported to contain gold in paying quantities at Acklens farm, a name given to a portion of the bench on the right limit of the Klondike, 2 mi above its mouth; they are, however, generally of little economic importance.

The 'high level creek gravels' or 'White Channel gravels' are ancient creek deposits laid down in the wide, flat-bottomed valleys, which characterized the region before the last general uplift. After their deposition, the country was elevated 600 to 700 ft, and the increased grades acquired by the streams enabled them to cut down through their old gravel beds into the bedrock beneath, and to excavate the steep-sided troughlike valleys in which they now run. The old gravels now occur on wide benches bordering the present valleys at elevations of from 150 to 300 ft above them, the elevation generally increasing downstream. Their distribution along the valleys is irregular, as a large portion of the deposit was destroyed during the deepening of the main valleys and the tributary valleys and gulches.

The general character of the White Channel gravels is remarkably similar in the various Klondike creeks but differs considerably from the ordinary type of stream deposits in other parts of Yukon. They consist of a compact matrix of small, clear, little-worn and often sharply angular grains of quartz and scales of sericite thickly packed with rounded quartz pebbles and rounded and subangular and wedge-shaped quartz boulders often 2 to 3 ft in diameter. Flat and subangular pebbles of sericite schist, the principal rock of the district, are also present but in much smaller numbers than the quartz constituents. The schist pebbles are usually decomposed and crumble rapidly when thawed out. The deposit is always stratified, but, except in rare instances, there has been no sorting of the various constituents into separate beds, and the composition is very uniform throughout. The colour is characteristically white or light grey due to the preponderance of the quartz constituents and the leaching out of the greater part of the iron. The colour is darker and the sands are noticeably coarser towards the limit of the deposit on the upper part of the creeks.

The White Channel gravels vary in thickness from a few feet to 150 ft and in width from 100 ft to ½ mi or more. The deposit increases in volume descending the streams, and attains its greatest development near their mouths.

The deposits, unlike the creek and gulch gravels, appear to be destitute of vegetable and animal remains. None were found by McConnell (1905) and the few reported discoveries by miners lack confirmation.

On Gold, Adams and other hills on Bonanza Creek the typical compact white variety of the White Channel deposit is replaced towards the sides of the old valley by flat rusty coloured gravels, more loosely bedded and containing a smaller proportion of quartz than the ordinary white variety. These probably represent flood plain deposits. They have the appearance of overlying the white variety and were formerly, in the absence of sections, considered by McConnell to be younger. However, the long exposures, now available for study in the various hydraulic cuts, show that the two varieties pass gradually one into the other both horizontally and vertically and in places are interbedded, evidence of nearly contemporaneous deposition. The loose yellow variety seldom carries much gold.

McConnell (1905) concluded that the White Channel gravels were probably deposited by winding streams with easy grades and comparatively slack currents. The preponderance of vein quartz pebbles and boulders, the most resistant rock in the district, gives them the character of a residual deposit. They were built up slowly and in the long process the softer rocks were mostly destroyed and carried away.

The great length of the White Channel period is indicated by the enormous gold accumulations, all derived from the slow breaking up of auriferous quartz veins that took place in it. Since the close of the period the additions to the supply have been trifling, although a sufficient time has elapsed to enable small streams to excavate channels, mostly through hard schists from 300 to 600 ft in depth. Practically all the gold in the present low level valley flats is of secondary origin and derived from the partial distribution of the older gravels.

The age of the White Channel gravels has not been determined, but they must date back to the Pliocene at least. They were certainly deposited before the advent of the present severe climatic conditions, as the white coloration is largely due to the leaching out of the greater portion of the iron by circulating surface waters, and this must have taken place before they were permanently frozen.

Summarizing we can say that the gold in the Klondike placers has passed through at least four stages of concentration as follows: (1) primary concentration in quartz veins and other bodies; (2) secondary concentration in the oxidized zones of the quartz veins and other auriferous bodies; (3) tertiary concentration in the placers of the high level White Channel gravels; and (4) quaternary concentration in the low level gulch, creek and stream gravels.

Each of these stages has resulted in a successive enrichment, the last stage being phenomenally rich in some creeks.

The rich pay streaks in the White Channel gravels invariably occur in the first few feet above the bedrock or in the upper foot of the bedrock. False bottoms are rare. The remainder of the gravels are slightly auriferous carrying a few cents per yard. In the low level creek, gulch and river gravels and in the terrace gravels the pay streaks are commonly on the bedrock in the first few feet of gravel and weathered debris. Where the bedrock is tight the thin stratum of gravel immediately above the bedrock is exceedingly rich. Where the bedrock is open the first few feet of the bedrock and the first few feet of the overlying gravels constitute pay material. In some places in a few creeks the shattered and frost wedged schist layers of the bedrock near the erosion surface contained all of the gold, the overlying gravels being practically barren. Most of the pay streaks in the Klondike were remarkably persistant in length, wide, some up to 1000 ft or more, and exceedingly rich. The one in the low level creek gravel of Eldorado Creek for instance ran some 65 oz per running foot for 4 mi.

The gold of the pay streaks is variable both in appearance and fineness. Near the heads of streams and in the gulches and draws the gold in the low level gravels occurs as coarse, commonly angular grains, flakes, sprigs and wires, and as nuggets that are fairly large. Farther downstream the gold particles are more rounded, flattened, finer grained, and large nuggets are uncommon. The gold in the White Channel gravels ranges from fine grained to relatively coarse, rough flakes, wires and particles. Nuggets are common but not generally very large. In both types of gravels, low and high level, the gold commonly has a crystallized character, and some of the nuggets enclose quartz or are partly enclosed by this mineral. The quartz is identical with that seen in the gold-bearing quartz veins, blows, etc. according to the writer's observation. Dendritic gold occurs in places on pebbles and stones in the placers, and crystals are not uncommon.

Mustart (1965) and Gleeson (1970) give spectrographic analyses of gold from a number of the creeks. All samples report Ag, Cu, Hg, Ti, Mg, Al and Fe, and some contain traces of Pb, As, Sb, V, Ba and Sn. Mustart noted an unidentified Au-Sn-Pb compound in gold from Monte Cristo Hill, Bonanza Creek.

The fineness of the Klondike gold is exceedingly variable not only on different creeks but also along different portions of the same creek. The lowest fineness recorded appears to be about 625 and the highest 890. McConnell (1907) concluded that the grade of the placer gold appeared to depend mainly on original differences in the grade of vein gold. He wrote:

> The variation in grade of the placer gold appears to depend mostly on original differences in grade of the vein gold from which it was derived. Creeks draining certain areas in the district carry low grade gold, while other areas supply high grade. An important centre of dispersion for low grade gold occurs west of the lower portion of Hunker Creek. Hester and Last Chance Creeks, Henry Gulch and Bear Creek all head in the same ridge within a comparatively short distance of each other and all carry low grade gold. Big Skookum Creek, a tributary of Bonanza Creek, heads in a low grade area and the gold brought down by it lowers appreciably the general grade of the Bonanza Creek gold for several claims. The Dome and surrounding region furnishes a good example of a high grade area. The streams flowing outwards from this centre, including Upper Dominion, Upper Hunker, Sulphur and Gold Bottom Creeks, all carry high grade gold although the values differ considerably.

McConnell (1907) also thought that there was an increase in the fineness of some of the gold due to leaching out of silver from the near surface parts of the nuggets. We shall return to this problem later.

Gleeson (1970) studied the minerals accompanying gold in the Klondike placers. The most abundant suite in the low level creek gravels included actinolite, barite, chlorite, epidote, hornblende, hypersthene, garnet, goethite, ilmenite, leucoxene, magnetite, pyrite, sphene, rutile, tremolite, tourmaline, zoisite and zircon; the less abundant to rare suite composed andalusite, anatase, apatite, biotite, cerussite, chromite, clinopyroxene, clinozoisite, dolomite, jarosite, micrometeorites, fluorite, kyanite, olivine, spinel, staurolite, topaz, monazite, scheelite, sphalerite and cassiterite. The heavy minerals in the White Channel gravels are the same but slightly more rounded. Highly resistant minerals such as garnet, magnetite and zircon are generally more plentiful than the softer minerals such as barite, goethite, pyrite and jarosite.

The origin of the gold in the Klondike placers has long been debated because few sizeable and rich primary gold-bearing deposits have ever been found in the district. McConnell (1907) originally considered that the gold came from the quartz deposits in the district, a view that is essentially correct in the writer's opinion.

There are a number of facts which support the view that most of the gold came from the quartz deposits, including the blows, stringers, etc. that are probably metamorphic secretion products and are younger than the quartz-barite and quartz sulphide veins mentioned above. These facts can be enumerated as follows:

1. All of the quartz-bearing deposits are auriferous. Some carry visible gold, occasionally in spectacular amounts.
2. The gold nuggets with quartz indicate that at least some of the gold came from quartz deposits. The quartz in the nuggets can be matched with that in the primary quartz deposits in the writer's opinion.
3. A number of the heavy minerals accompanying the gold in the placers evidently came from the gold-bearing veins. Barite is one of these diagnostic minerals, galena is another. Some of the pyrite in the placers matches that in the veins, and some came from the pyritic graphitic schists.
4. There is a general spatial relationship between the gold placers and the areal distribution of the Klondike Schist and the gold-bearing deposits it encloses. (Fig. 76). This suggests that the vein deposits, and probably also some of the rocks such as the pyritiferous graphitic schists, gave rise to the gold placers.

It seems probable, basing conclusions on these facts, that the gold came mainly from the quartz deposits enclosed within the Klondike Schist. The amount of quartz as a rough estimate in the Tertiary White Channel gravels as originally laid down probably exceeded 6×10^9 tons which at 0.01 oz Au/ton of quartz according to our average analyses would yield about 60 million ounces of gold of which say one half, or 30 million ounces were released to accumulate in the modern gulch and stream placers. If we add gold which would have been released during Tertiary time from the weathered pyrite in the country rocks, especially the graphitic schists, the amount of gold for placer concentration in the White Channel gravels would be greatly augmented.

The Cariboo, British Columbia. The Cariboo, with Barkerville its capital, was the premier placer gold district of British Columbia. It lies in the central part of the province within the intermontane plateau region bounded by the Coast Range on the west and Cariboo and other mountain ranges on the east. The placer gold production of the district is probably of the order of 2.5 to 3 million ounces.

The Cariboo is a deeply dissected region with low rounded hills and an irregular pattern of streams, creeks and gulches. The weathering and erosion that gave rise to the dissection of the country evidently originated in early Tertiary time and extended throughout that period. In Pleistocene time a stagnant ice sheet lay over the land, removing much of the weathered mantle at higher elevations but having little effect on the placer deposits in most of the valleys. The bedrock is folded and faulted phyllite, quartzite, argillite, slate and limestone of the lower Paleozoic Cariboo Group. These enclose a host of quartz bodies ranging from stringers, blows and boudins to fairly well-defined quartz-vein zones and siliceous replacements in the limestones. All these deposits are auriferous, some of the vein zones and siliceous replacements having been mined extensively (see page 281). The principal minerals in the auriferous deposits are pyrite, galena, chalcopyrite, sphalerite, cosalite, bismuthinite, arsenopyrite, pyrrhotite, scheelite and free gold. Details of the geology of the Cariboo district are given by Hanson (1935) and Sutherland Brown (1957); the placers are described at length by Johnston and Uglow (1926).

The placers of the Cariboo (Barkerville) district, discovered in 1860, are now largely exhausted after having yielded probably over 2.5 million ounces of gold. The principal productive creeks were Williams and Lightning, but a number of shorter creeks produced considerable quantities of gold (Fig. 78). Several types of auriferous gravels are found in the district, and the gold has had a complex history following its release from the deposits and rocks during extensive oxidation and erosion in Tertiary time. First there was an extensive accumulation of gravels and gold in the valleys during a

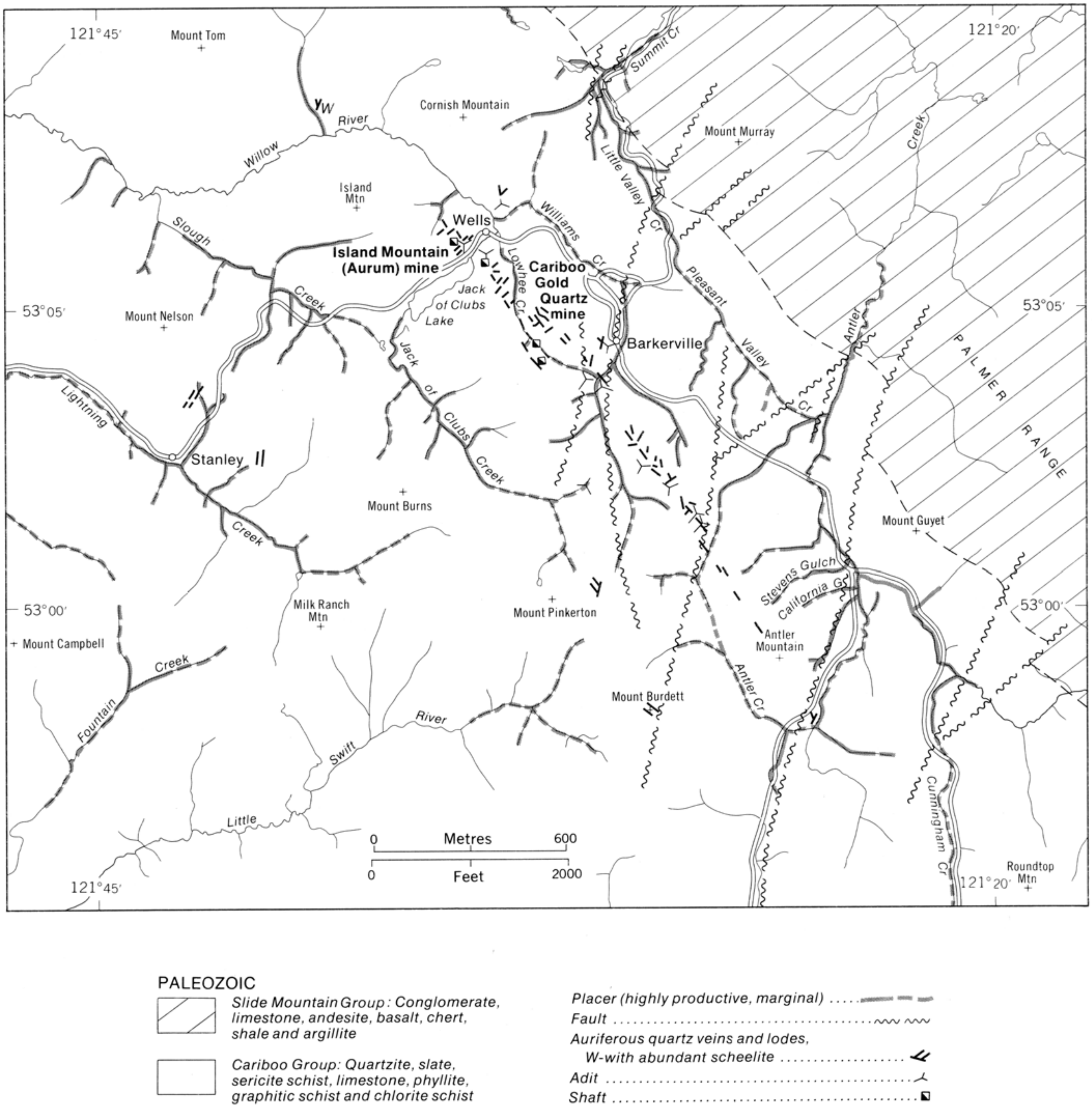


Figure 78. Generalized geological map of the Barkerville (Cariboo) district showing relationship of the auriferous placers to the bedrock gold veins (after Johnston and Uglow, 1926; Hanson, 1935; Sutherland Brown, 1957; with additions by the writer from field observations and airphotos).

gradual period of Tertiary uplift. This was followed in Pleistocene time by the development of valley glaciers and stagnant ice sheets, the latter largely protecting the Tertiary gravels from scouring and destruction. During interglacial periods some gold placers were formed probably from reworked gravels at the heads of valleys. In addition some outwash deposits with some gold were formed in places from the sluicing action of the meltwater on the glacial debris and old gravels. Slight uplift after the disappearance of the glaciers rejuvenated the streams, and some have cut down and eroded the drift deposits yielding postglacial gravels that are slightly auriferous in places. Briefly the types of auriferous gravels corresponding to the various periods are as follows with accompanying notes:

1. *Ancient stream gravels resting on bedrock in the valley bottoms and on rock benches or in old channels.* These averaged about 5 ft in thickness and were the richest and most important of the auriferous gravels. They consisted of weathered and water-worn pebbles of country rock and considerable amounts of old talus or scree. Quartz pebbles were comparatively rare. The pay streaks were relatively persistent in length, developed mainly in the narrow, deep parts of the creeks and were mainly on the bedrock or in the upper few feet of the weathered and shattered rock. The gold was mostly coarse, very little flour or fine scale gold being present. Flattened grains, pellets and small nuggets of gold predominated, but there were also some crystals, angular particles, mammillary nuggets and quartz nodules with veinlets of gold. The accompanying heavy minerals of interest were pyrite, galena, scheelite and barite. The gold in these gravels was concentrated during Tertiary time, and the gravels were covered by glacial drift, in places up to 250 ft deep, in Pleistocene time. During Pleistocene time some of the Tertiary gravels were reworked giving rise to those described below.

2. *Interglacial stream gravels.* These are generally thought not always underlain and overlain by glacial drift. In most valleys they occur above a false bottom of boulder clay well above the bedrock of the creek. Most of the gold appears to have come from the reworking of ancient (Tertiary) gulch and creek gravels near the heads of the valleys and from glacial drift (eluvium) scraped off the adjacent hills. The gold in these gravels is essentially the same as that mentioned for the ancient stream gravels. Most of the pay streaks were lean but fairly extensive.

3. *Auriferous glacial outwash gravels.* These occur in irregular masses included in the glacial drift and to some extent in glacial gravels filling parts of the stream valleys. The gold is highly disseminated through these gravels, and pay streaks of value do not seem to occur in them.

4. *Postglacial stream gravels.* These have been derived mainly from the erosion of the glacial drift and ancient (Tertiary) auriferous gravels. They were deposited in places in the beds and along the benches of the present streams. Some were productive, but the pay streaks were thin. Some of the gold in the surface gravels on the benches was fairly coarse, but as a general rule the gold in most of the postglacial stream gravels was fine grained and commonly scattered through the gravels.

The placer gold of the Cariboo varied in fineness from about 775 to about 950 as compared with the vein gold which varied from 850 to 910. Johnston and Uglow (1926) found no evidence that the placer gold was, as a rule, of greater fineness than the vein gold. They considered that most of the gold was detrital and supported their view with evidence similar to that recorded above for the Klondike. They noted gold-rich rims on the nuggets, which they thought was due to leaching of silver. They thought that perhaps some of the placer gold resulted by accretion processes in the gravels, but concluded that this mode of origin was probably of little importance in the overall formation of the placers.

The precise source of the gold in the Cariboo placers is uncertain. The northwesterly trending vein zones that cut the rocks west of Wells and Barkerville (Fig. 78) may have provided much of the gold in Williams Creek and its many tributaries and that in Stevens Gulch, California Gulch and other gulches draining the Antler Mountain area. The source of the gold in Lightning Creek, Jack of Clubs Creek and the left limit tributaries of Slough Creek remains undetected. There may be a series of northwest trending vein zones that underlie the heavily drift covered area Mount Pinkerton–Mount Burns–Mount Nelson.

Other British Columbia placers. A number of other placer areas in British Columbia (Fig. 79) are of interest since they exhibit features that differ in some respects from the normal placers of the province. In the Atlin district, a deeply dissected and glaciated plateau is underlain mainly by sedimentary, volcanic and intrusive rocks ranging in age from Precambrian to Pleistocene (Aitken, 1959). The placers are stream placers found in an area containing base metal sulphide deposits and myriad quartz veins carrying some gold. The auriferous stream gravels are of two kinds: (1) yellow, highly decomposed gravels, some probably of Tertiary age, others of pre-Wisconsin interglacial age and generally buried beneath glacial drift, and (2) postglacial gravels formed by stream erosion of glacial drift and ancient gold-bearing gravels. The first type includes the important economic gold placers. They also carry some wolframite in places (e.g., Boulder Creek). Some of the auriferous gravels occur beneath Tertiary and Pleistocene basalts and scoria and in this respect are similar to the deep leads of Victoria, Australia. In the Cassiar district stream and river gravels in the Dease Lake area are similar to those at Atlin. The main auriferous rivers and streams were Dease, Thibert, McDame and Goldpan (Hanson and McNaughton, 1936; Gabrielse *et al.*, 1962). In places east of Dease Lake and along the Stikine River above Telegraph Creek, slightly auriferous stream and river gravels underlie basaltic lavas that are apparently Pleistocene in age.

In the Princeton district of central British Columbia the underlying rocks are a succession of volcanics ranging in age from late Paleozoic to late Tertiary; sedimentary rocks, mostly in minor amounts, interbedded with the volcanic groups; and intrusive rocks ranging in composition from granite to peridotite and in age from Jurassic to late Cretaceous or early Tertiary (Camsell, 1913; Rice, 1960; Raicevic and Cabri, 1976). The most interesting placers of the area occur in the Similkameen and Tulameen rivers. These carry both gold and platinoid minerals accompanied by chromite, magnetite and occasionally native copper. The ratio of platinoids to gold is about 1 to 4 in the Similkameen River and lower reaches of

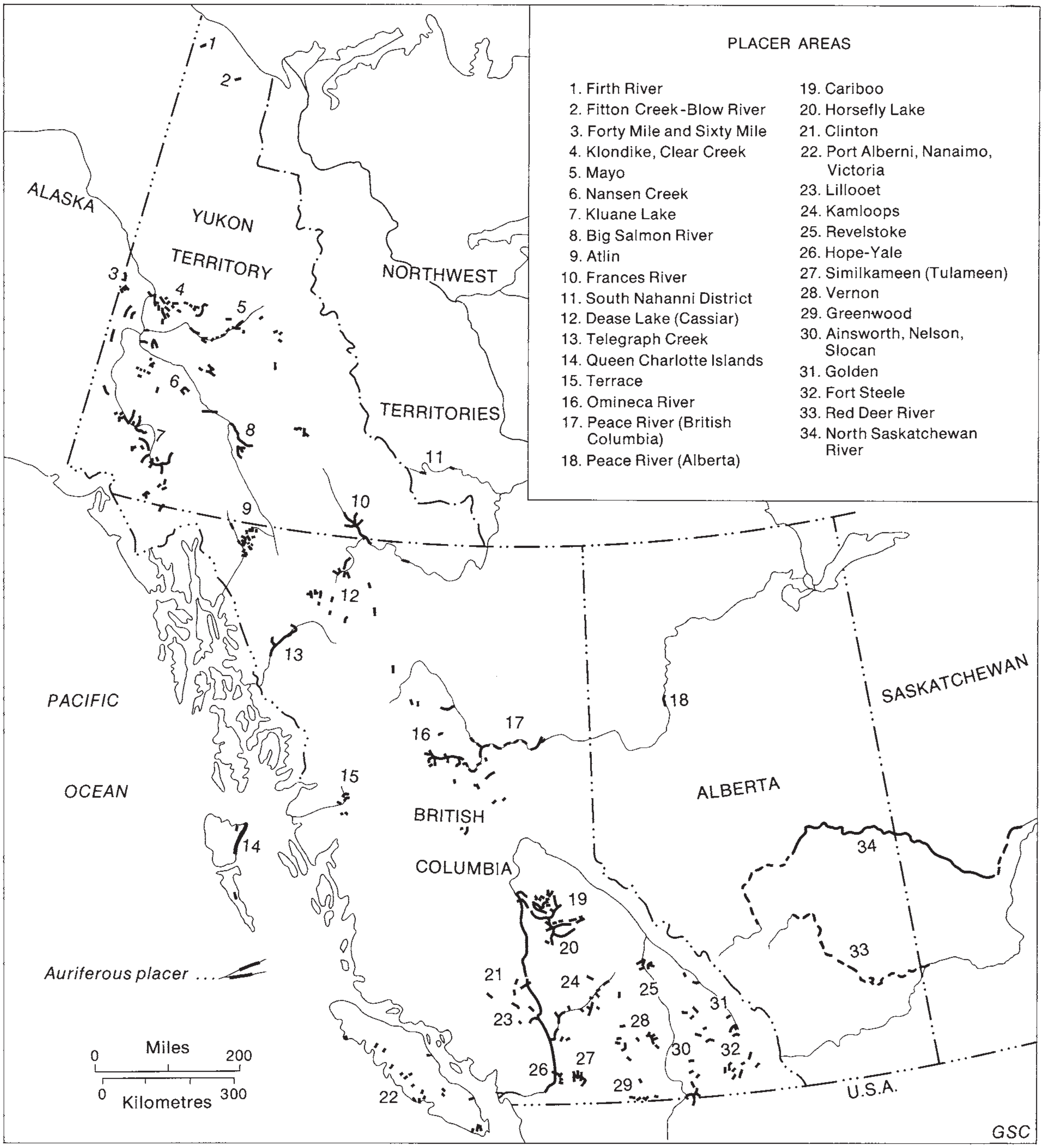


Figure 79. Placer gold districts in western Canada.

the Tulameen River, but increases upstream to a point where the platinoids equal and in places exceed the amount of gold. The platinoid minerals (some 19 in number; Raicevic and Cabri, 1976) are mainly isoferroplatinum, native platinum, ferroan platinum, tulameenite, iridosmine, osmium and rutheniridosmine. The gold, as described by Camsell (1913) and Rice (1960), occurs in rough, angular or slightly flattened, rarely well-flattened nuggets. Flour gold is comparatively scarce. The largest nugget reported weighed about 8 oz, but nuggets over 1 oz in weight are rare. Quartz can be seen adhering to occasional nuggets, and this and the general lack of flattening suggest that the gold has not moved far from its source. The platinum nuggets are not generally flattened and rarely even subangular, but occur in small rounded grains resembling fine shot, and mostly of relatively uniform size. These nuggets are smaller than the gold on the average, but at the same time the platinum does not occur in fine, flaky particles. Most of the pelletlike nuggets have a rough pitted surface, many show adhering grains of chromite and magnetite, and olivine and pyroxene are occasionally attached to them.

Commenting on the age and origin of the gold and platinum placers Rice (1960) had the following to say:

> The original source of the gold and platinum in the placer deposits is believed to be the gold-bearing veins of Grasshopper Mountain and vicinity and the Olivine Mountain body of platinum-bearing ultrabasic rocks. Erosion of these bodies has released their metal content, but it is evident that only the residue of a large amount of such rocks could have produced the rich deposits of Tulameen and Similkameen Rivers. Since glacial time canyons have been cut in the floors of some of the valleys, but over most of the area erosion has not succeeded in removing the mantle of glacial material, much less eroding any quantity of the underlying rock. It is, therefore, clear that the gold and platinum of the placers must have been released from the parent rocks by erosion in pre-Glacial time and deposited in pre-Glacial placers. It also follows that these placers must have partly escaped the dissipating effect of glaciation, and that the present deposits are mainly either remnants of pre-Glacial placers or those only slightly disturbed by the ice. There has, of course, been some reconcentration of the earlier deposits in the beds of the present streams, but it seems most unlikely that Glacial and post-Glacial streams could have formed the rich placer deposits of the Tulameen except by reworking deposits that were already rich.

Chaudière River basin, Quebec. The gold placers of the Beauceville area, in the Chaudière River drainage area, 50 mi southeast of Quebec, were discovered circa 1830 and since that time have yielded about 100 000 oz of gold. By comparison these placers were small, but they are of interest since they occur in a glaciated terrain of eastern Canada.

The bedrocks are of Ordovician age, belonging to the Beauceville Formation and Caldwell Group and include folded and faulted argillites, quartzites, slates, tuffs and basic volcanics, all containing relatively large amounts of pyrite. Innumerable quartz bodies occur in all of these rocks especially in the quartzites, in every conceivable form – as contorted masses, as lenses and veins in fractures and small faults and as blows, boudins and irregular masses. Some carry carbonates and pyrite; other sulphides such as arsenopyrite, chalcopyrite and galena are rare. No gold was seen in any of the quartz bodies by the writer, but channel samples taken for analyses reported from 0.01 to 0.02 ppm Au. The sedimentary rocks reported less than 0.01 ppm Au, but pyrite separated from these rocks contained up to 0.4 ppm Au with an average of about 0.025 ppm Au.

Details of the general geology of the Beauceville area are given by Cirkel (1911), MacKay (1921), Tolman (1936), Gorman (1955) and Béland (1957). The surficial geology is reported on by Gadd (1964). The placers are described in detail by MacKay (1921).

The Beauceville area lies within the Chaudière basin, which is characterized by deeply dissected uplands with low rounded hills, wide valleys and rock terraces marking stages in the lowering of the valleys, all features denoting an area of mature topography. The final stages of the sculpturing of the terrain were evidently accomplished in Tertiary time and were followed during the Pleistocene by extensive glaciation, which has left a mantle of glacial till and other deposits over much of the area. Two directions of glaciation are evident, both resulting from a general south to southeastward movement of the ice. In valleys lying in the general direction of the ice movement the gold placers were destroyed, whereas in the smaller valleys with axes across the direction of movement of the ice the auriferous gravels were preserved and covered with glacial drift.

Considerable amounts of gold have been won from three rivers in the area, including in their order of importance Rivière Gilbert, Rivière du Moulin and Rivière des Plantes and in small amounts from the following water courses; rivières Chaudière, Famine, Linière, Metgermette and Cumberland and ruisseaux Bolduc, d'Ardoise and Stafford (Fig. 80). The surficial deposits in all of these watercourses consist of a lower series of gravels, richly auriferous in places, overlain by glacial sands, gravels, boulder clay, till, etc. that have been reworked and redeposited in most streams and rivers as shallow stream gravels. A section through the surficial deposits in Rivière Gilbert, as given by MacKay (1921), shows the following sequence:

	Thickness
Surface	(ft)
Loam and river gravel	4
Hard, blue boulder clay	36
Hard grey sand	23
Firm grey sand	10
Gravel and sand	14
Ferruginous sand	3
Auriferous gravel	7
Bedrock	

A section across Rivière du Moulin at the hydraulic pit is shown in Figure 81.

There are differences of opinion among investigators as to the origin and age of the rich gold gravels in the bottoms of the rivers and streams. MacKay (1921) considered them to be of Tertiary age derived largely from deep erosion during that time. He noted that some of the gravels were cemented by iron oxides (limonite), a criterion he thought indicated Tertiary derivation. Gadd (1964), however, considered that the gold-bearing gravels belong to the nonglacial sand and gravel sequence that are no greater than interglacial in age and probably interstadial. He noted that some of these gravels and sands rest on older till and in turn are capped by younger till

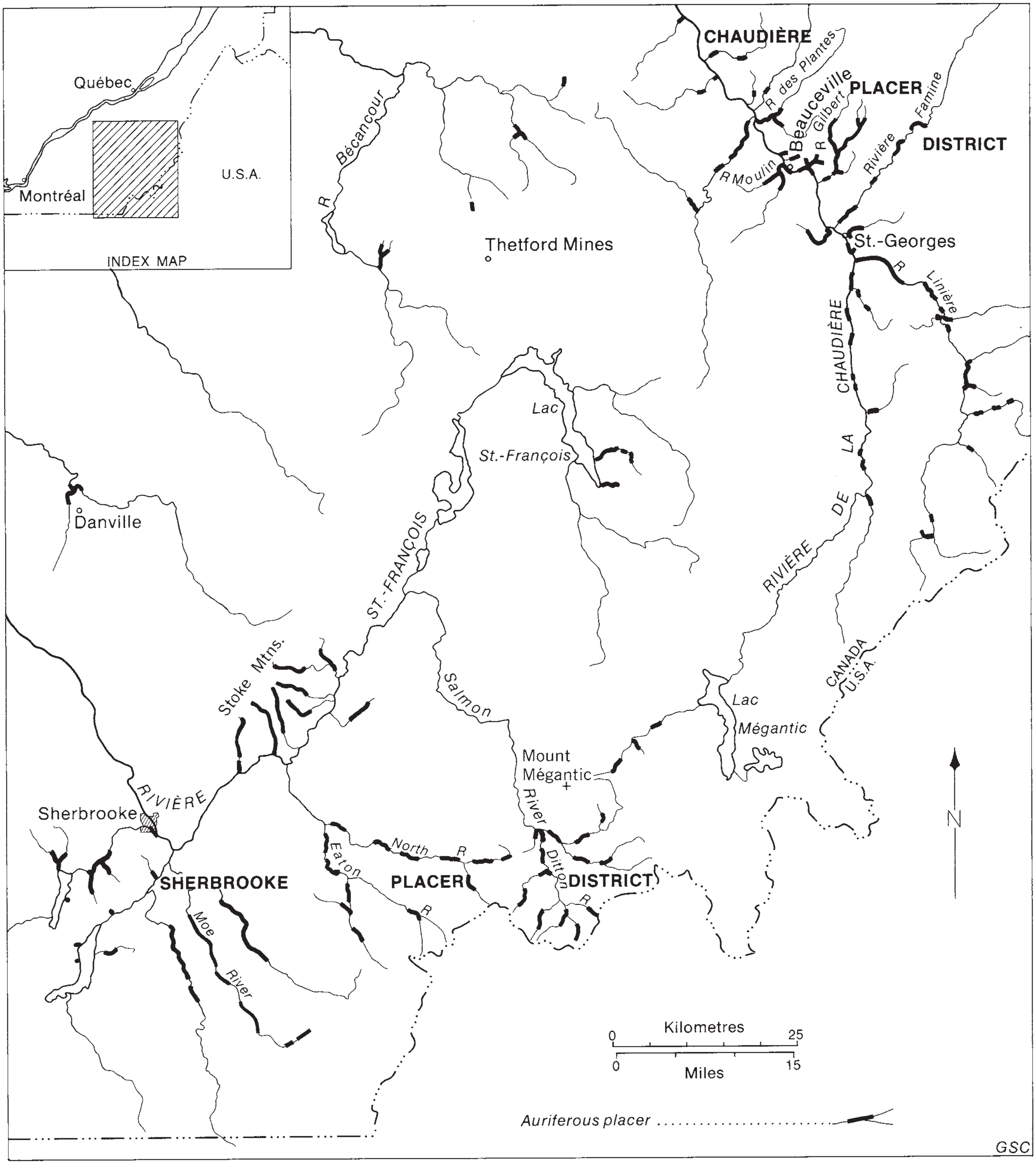


Figure 80. Auriferous placers of southeastern Quebec.

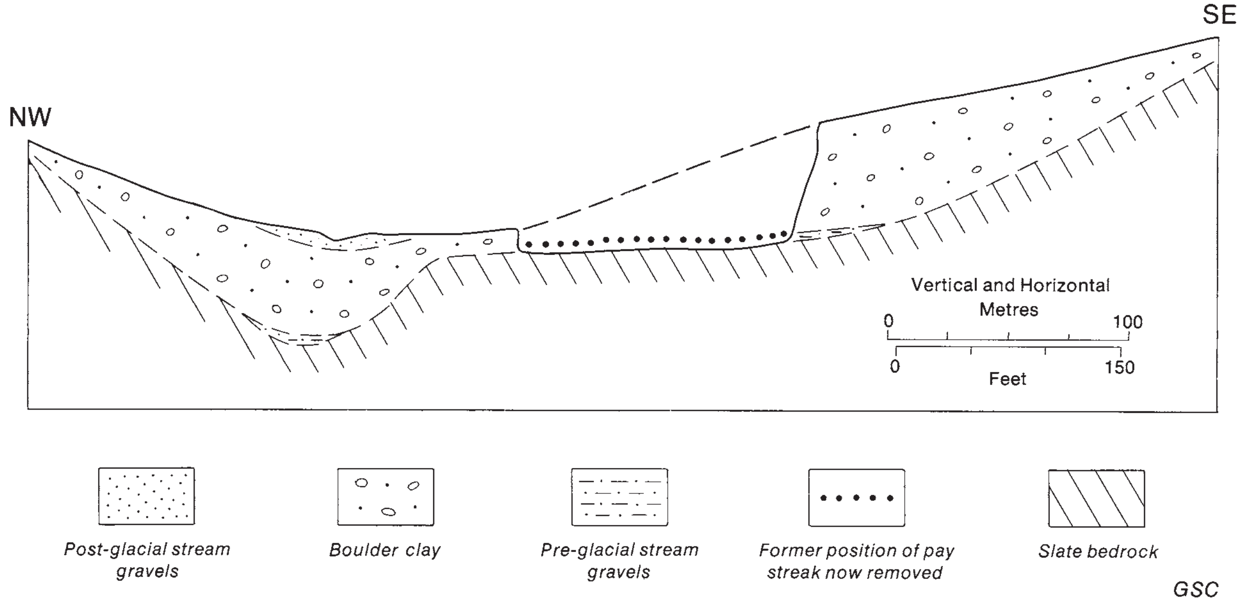


Figure 81. Cross-section of auriferous placer in Rivière du Moulin, Beauceville district, Quebec (after MacKay, 1921).

of the region. The cementation and iron oxide staining of some of the gravels were considered to be phenomena of secondary enrichment under groundwater conditions of present or relatively recent time.

It is difficult to reconcile these opposing views. The observations of the writer show that the cementation phenomena of the sands and gravels by iron oxides is proceeding today, being related to a number of springs at the heads and in the tributaries of many of the gold-bearing streams and rivers. Their waters carry iron, evidently derived from the weathering of the pyritiferous schists, slates and phyllites, which precipitates in the sands and gravels under slightly oxidizing conditions. Cementation phenomena cannot, therefore, be related exclusively to the Tertiary. On the other hand the materials of the gold-bearing gravels represent materials from a deeply weathered and eroded terrain, and these have taken time to form, much longer than an interglacial period. The evidence of the gold pay streaks suggest a very long period of accumulation and winnowing of the metal. The nuggets, especially, are highly knarled, rounded, abraded and pitted and have been a part of the dynamics of the erosion cycle for a long time. All this suggests that the gold, its accompanying heavy minerals and the weathered products with which it is associated were largely accumulated in the eluvium and drainage systems in pre-Pleistocene (probably Tertiary) time. During Pleistocene time these materials have been reworked in part and probably some of the gold has been mechanically redeposited.

MacKay (1921) divided the placers of the area into preglacial and postglacial categories. The former may now be considered as interglacial, at least in part. Brief descriptions of each follow.

Preglacial (interglacial) placers. These constitute the chief sources of gold and include stream bed placers, terrace or beach placers, river bar placers and alluvial plain placers. Only the stream bed and terrace placers have been productive. The average thickness of the auriferous gravels in these deposits was 5 ft, although some are over 30 ft thick. Most of these gravels are yellow, oxidized, compact and frequently cemented (limonite-cemented sands and gravels). Underlying the gravels in places is a yellow oxidized unctuous clay. The gravels contain stones and boulders up to 2 ft in diameter that are said by MacKay (1921) not to be glaciated and all of local origin. The writer would agree with this conclusion.

Analyses of the limonite-cemented gravel and sand and the puttylike clay from Rivière Gilbert are given in Table 69.

Table 69. Analyses of limonite-cemented conglomerate and sand and limonitic clay from Rivière Gilbert, Beauce County, Quebec

Constituent	Limonite-cemented conglomerate and sand	Limonitic clay
	(%)	
SiO_2	66.2	67.2
Al_2O_3	11.7	15.3
Fe_2O_3	9.4	4.1
FeO	1.5	0.7
CaO	0.7	0.4
MgO	1.6	1.2
Na_2O	2.4	2.0
K_2O	1.9	2.7
H_2O (total)	3.7	4.0
TiO_2	0.59	0.66
P_2O_5	0.13	0.09
MnO	0.07	0.06
CO_2	<0.1	<0.1
S	0.06	0.02
F	0.02	0.04
Cl	0.02	<0.02
C	0.23	0.11
O ≡ Cl, F, S	0.03	0.03
Total	100.2	98.6

Both the limonite cemented gravel and clay contain relatively small amounts of gold (<0.01 ppm). Heavy concentrates from these materials, however, show the following gold values:

	Au (ppm)
Limonite-cemented sand and gravel	0.02
Limonitic lower clay	0.30

The gold values are disseminated through the gravels in places, but more generally they are in the material immediately above the clay. Where the clay is missing the values are on the bedrock and/or in the upper few feet of bedrock. The gold occurs as fine dust and in nuggets ranging up to the size of goose eggs. Most nuggets are highly water worn, but a few of the smaller ones show angular outlines. Some contain vein quartz. The heavy minerals accompanying the gold are magnetite, specularite, hematite, chromite, ilmenite, pyrite, garnet, rutile, zircon, ottrelite, corundum and platinum. The platinum occurred in only minor amounts in Rivière des Plantes. It and the chromium probably derived from the ultrabasic rocks in the basin of this watercourse.

Postglacial placers. These include stream bed placers, terrace or bench placers, river bar placers and alluvial plain placers in the modern and postglacial sands and gravels. The first gold found in the area was in the river bar and alluvial plain placers of the Chaudière down river from Rivière Gilbert. The gold is generally fine grained in these deposits and commonly highly disseminated through the gravels. Only an occasional nugget is found. None of these placers were of importance except where the yellow (interglacial or preglacial) gravels were exposed to stream cutting, and while these were rich they were pockety. The heavy minerals in these placers are the same as those mentioned above for the preglacial and interglacial gravels.

MacKay (1921) and others thought that the gold in the Beauceville placers was concentrated during Tertiary time from relatively local sources. Logan and Hunt (*in* Logan *et al.,* 1863) writing earlier, however, removed the source to the crystalline schists of the Notre Dame range lying north of the Beauceville area. Cirkel (1911) considered that the source of the gold lay outside the placer area. The writer considers the source to be the rocks and quartz deposits of the Beauceville Formation and Caldwell Group within which the gold-bearing streams occur. There is certainly enough gold in the pyrite alone of these rocks (up to 0.4 ppm) to provide the gold in the placers.

In other parts of the Eastern Townships (Fig. 80) and Gaspé of Quebec small gold placers are known, and some have been worked in the past (Dresser and Denis, 1949). According to McGerrigle (1936) all the placers in the Eastern Townships, including those in the Chaudière Valley, lie southeast of the Sutton range and between St. Francis-Massawippi Valley on the southwest and the vicinity of the Chaudière River in the northeast. Areas, excluding the Chaudière Valley, where gold has been washed or recorded, include the Ditton River and Moe River basins in Compton County, the Stoke Mountain area in Richmond, Wolfe and Compton counties and others, described in some detail by McGerrigle (1936). He recognized three types of placer gold deposits: pre-Glacial, Glacial and Recent. The pre-Glacial deposits, exemplified by those in the Ditton River and Stoke Mountain areas, occur mainly in the stream bottoms in brownish weathered materials, often in a yellowish clay. They are probably of Tertiary age. The Glacial deposits are in sands and gravels filling parts of the stream and river valleys (e.g., Ascot Township). The Recent deposits were formed after the melting of the ice sheets and include those that have resulted from the reworking of older deposits by the present streams, as in gravel and sand bars along the rivers and streams (e.g., Moe River). Most of the gold in the deposits is well worn, fine grained, scaly (dust) and tarnished to bright in colour and lustre. A few small nuggets have been recovered, and some streams contain rough angular particles and dendrites. Some of the nuggets in the Ditton River contain inclusions of hessite. The principal heavy minerals encountered with the gold include magnetite, pyrite, galena and zircon.

McGerrigle (1936) considered that the gold in the placers was derived from quartz veins and probably partly from sedimentary bedrocks (conglomerates and quartzites). The fine-grained (dusty) nature of much of the gold suggests other possible sources. The district in which the placers occur is largely underlain by pyritiferous black phyllites and schists from which some of the gold probably originated during the course of weathering. Pyritic copper deposits, some auriferous, occur in a number of places in the Sherbrooke area. Weathering of these deposits may have given rise to some of the gold placers as is perhaps the case for those in Felton Brook, which heads near the Suffield, King, Howard and Silver Star copper sulphide deposits. Other gold placers whose source of gold is unknown may indicate similar sulphide deposits hidden beneath the heavy drift.

Sierra Nevada, California. The placers of the Sierra Nevada of California were discovered in 1848 after which followed the great rush of 1849. Since then some 55 million ounces of gold have been won from the placers that lie mainly on the southwestern flank of the Sierra Nevada along a distance of some 250 mi (Fig. 82).

The productive gravels of the Sierra Nevada are mainly of Tertiary and Quaternary age and are described at length by Lindgren (1911), Haley (1923), Pardee (1933), Jenkins and Wright (1934), Clark (1970) and Yeend (1974). Most of the rich placers are now exhausted and hydraulic mining of lean gravels was largely prohibited by law many years ago, because of environment problems in the basins of the Feather, Yuba, Bear, American and other rivers. Dredging along sections of the Yuba River (Hammonton district), American River (Folsom district) and elsewhere has, however, continued for some 70 years, terminating in 1968.

The general topography of California is simple – a mountain range along the ocean, the Coast Range; another along the eastern border, the Sierra Nevada; and between them closed in at both ends by their junctions a splendid valley in a tectonic trough, the Great Valley separated by the Sacramento River into the Sacramento and San Joaquin valleys. The part that concerns us is the northern part of the Sierra Nevada, the northern part of the San Joaquin valley and the southern part of the Sacramento valley (Fig. 83). The bedrock underlying this large area is mainly of Paleozoic and Mesozoic age consisting of highly folded and faulted sediments and volcanics intruded by ultrabasics (serpentinites) and granitic rocks.

Figure 82. Map showing the location of the principal placer districts of California.

Along extensive fault and fracture systems great gold-bearing quartz lodes were formed in late Mesozoic time; of these the Mother Lode system was the greatest. There followed then a long period of uplift and deep secular weathering and erosion that extended throughout most of the Tertiary. Much gold was accumulated in the streams that flowed southwestward off the Sierra Nevada. Near the end of Tertiary time volcanism was the dominant feature and most of the auriferous gravels were buried beneath rhyolite flows and tuffs that filled the valleys and in many places diverted the streams into new courses, some of which crossed the old courses. Some gold was deposited in these new courses. Near the end of Tertiary time vast eruptions of andesitic flows, tuffs and breccias took place filling all the valleys to their rims. New streams initiated as the result of marked uplift and tilting in late Pliocene and early Quaternary time cut deeply into these tuffs and other volcanic rocks, and into, and in many cases, below the auriferous Tertiary gravels. Great V-shaped canyons, some 3000 to 4000 ft deep, developed, and in many cases some of the gold was swept out into the valley at the foot of the Sierras, there to form large accumulations of gravels that have been extensively dredged in places (Fig. 83). Later in the Quaternary, mountain and valley glaciers developed, the latter mainly in the upper parts of the valleys. They had only a small effect on the redistribution of the Tertiary gold.

The present topography of the placer fields is a valley (the Great Valley) from which a foothills region rises abruptly, giving way first to a plateau or middle slopes, rugged in part and ultimately as one moves westward to the high Sierras with an average elevation of 6000 ft from which some high peaks and ridges rise well above the snowline. Through the foothills, middle slopes and high Sierras the streams have cut deep V-shaped canyons that widen out to U-shaped valleys in the high Sierras.

The placers first worked in the Sierra Nevada were in the auriferous gravels of the present streams, from which the gold was traced to the Tertiary river beds on the summits of the ridges and ultimately to the primary sources in the quartz veins of the Mother Lode and other systems. Here, we shall consider only the auriferous Tertiary gravels.

The nature and history of the Tertiary gravel deposits is best shown on Lindgren's classic section (Fig. 84), on which it is evident that considerable complexity exists. The location of the various courses of the Tertiary auriferous channels and the main intervolcanic (late Tertiary) channels of the Sierra Nevada are also shown in fascinating detail on the map by Lindgren (1911) from which generalized Figure 83 was largely compiled by Clark (1970). It will be seen that many of the Tertiary channels bear only a general relationship to the present channels, and that in many cases they cross the latter at large angles.

According to Lindgren (1911) the occurrence of gold in economic quantities in the Tertiary gravels depends essentially on the distribution of the primary deposits in the pre-Tertiary rocks of the Sierra Nevada. The Tertiary and Recent river courses are barren where traversing extensive granitic areas but carry values when they reach the flanking contact zones and sediments. The constituents of the Tertiary gravels are mainly pebbles and sands of quartz and metamorphic rocks, and the pay streaks are mainly on the bedrocks (Fig. 85). The gold is both coarse and fine, and large nuggets have been recovered from some channels. Lindgren (1911) did not think that chemical precipitation of gold was responsible for the formation of the nuggets. The fineness of the Tertiary channel gold is greater than that of the primary veins, an average of 900 for the former as compared with values ranging from 620 to 900 for the latter. The gravels in the richer channels ran from about 3.5 to about 25 oz Au/linear foot. The accompanying detrital heavy minerals in the Tertiary channels are magnetite, ilmenite, chromite, pyrite, monazite, zircon, garnet and small amounts of native copper, cinnabar, amalgam and platinoids, the last derived from the serpentinites of the gold belt. Detrital diamonds were recorded here and there, derived it is thought from the peridotites (now serpentinites). Among the authigenic minerals in the Tertiary placers Lindgren (1911) mentions calcite, dolomite, silica (opal and chalcedony) and pyrite, some auriferous. These minerals were evidently deposited by migrating groundwaters in the gravel channels, some probably heated during the volcanic periods. Fossils of many types lie buried in the gravels of the channels. They include Tertiary mammals, doubtful human remains and artifacts, fossil leaves, diatoms and abundant silicified fossil wood.

The Chocó, Colombia. The great placers of the Chocó and other districts in Colombia were first worked before the coming of the Conquistadores by native Indians using the calabash (gourd) and batea (pan). With the coming of the Spaniards gold was sought throughout Colombia, being found in practically every part of the country. Since mining began in 1550 more than 500 million dollars in gold has been won from the placer deposits. The Chocó, and the departments of Antioquia, Caldas and Tolima, were the most important New World sources of revenue for Spain during the 17th and 18th centuries.

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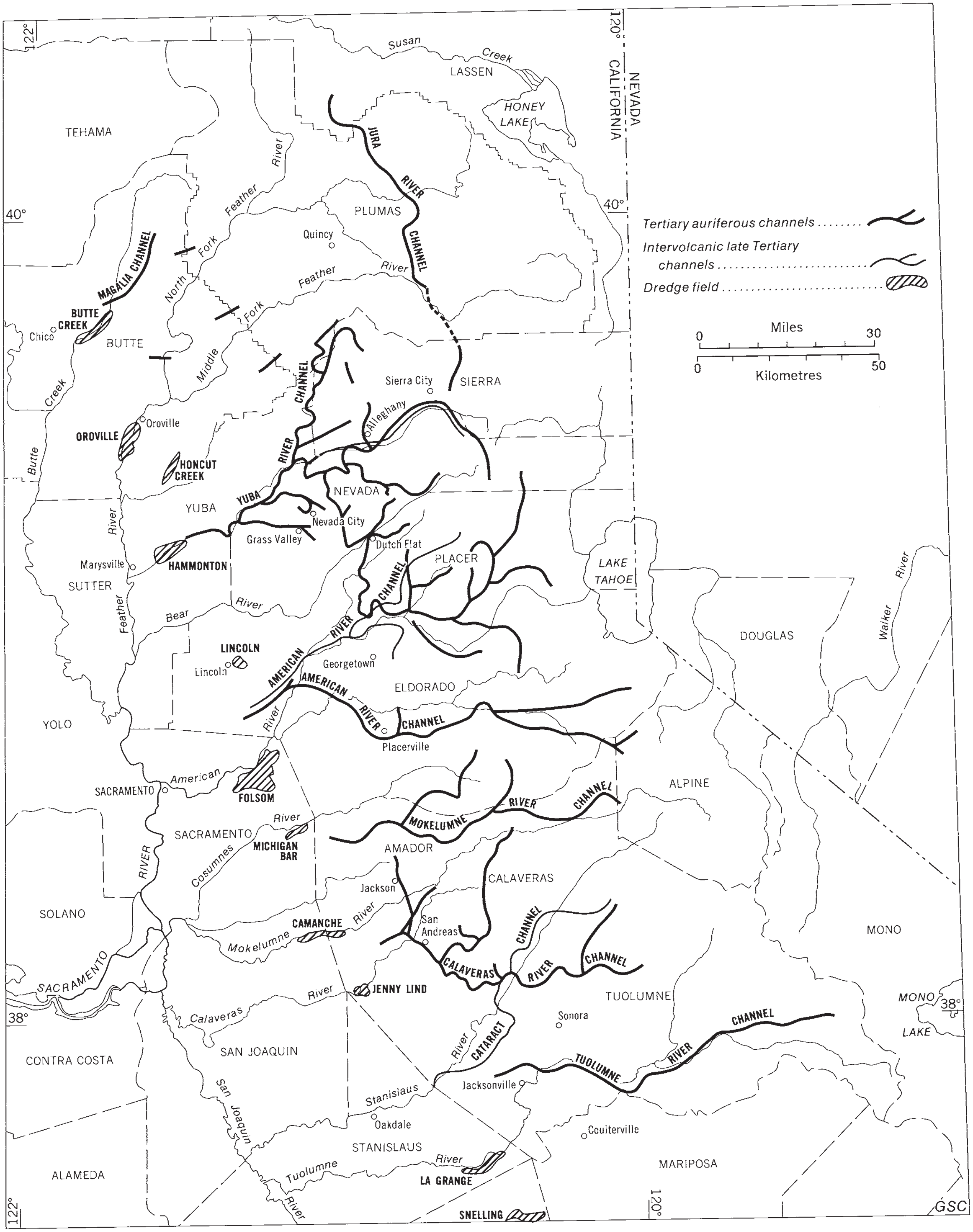

Figure 83. Map of Tertiary channels and dredge fields, Sierra Nevada, California (after Lindgren, 1911; and Clark, 1970).

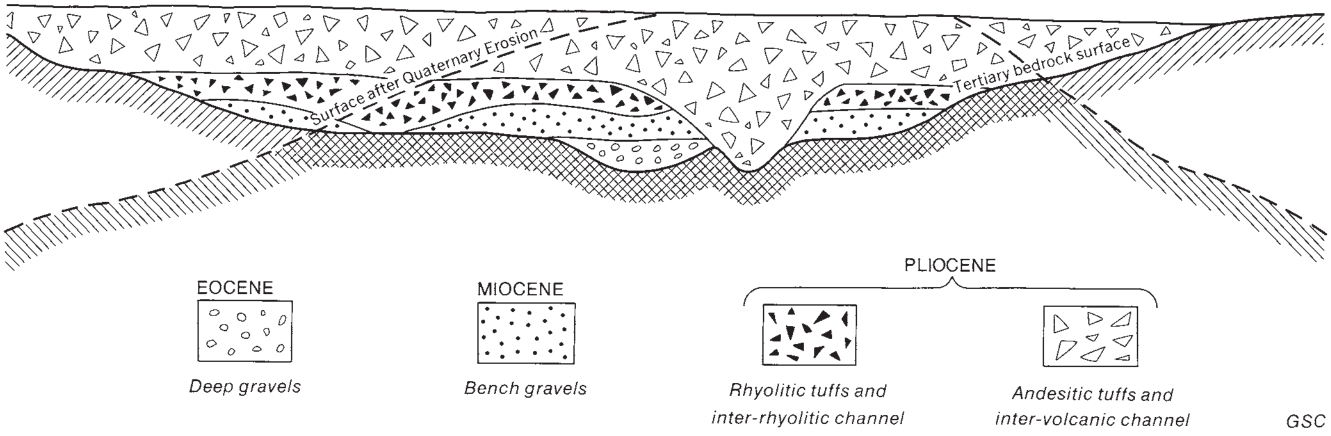

Figure 84. Schematic representation of the four principal epochs of Tertiary gravels in the Sierra Nevada, California (after Lindgren, 1911).

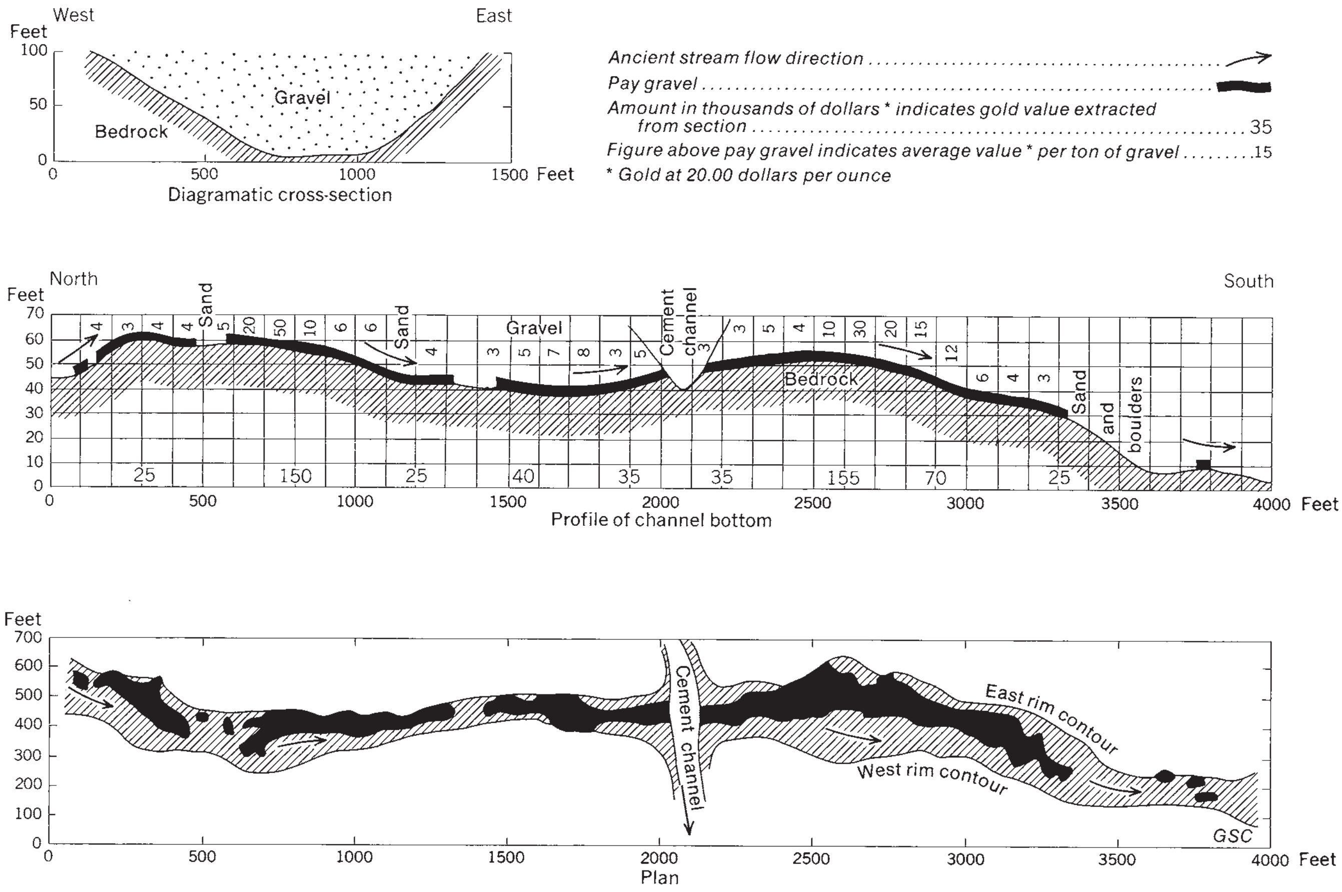

Figure 85. Section, profile and plan of part of the Mayflower channel, Forest Hill divide, Placer County, California (after Lindgren, 1911).

The Chocó is covered by thick forest typical of the tropical rain belt. The geological terrane is mainly Tertiary, consisting essentially of conglomerates, sandstones, shales and various types of volcanics and serpentinized basic intrusives. Quartz veins containing gold, silver, copper, lead and zinc are widespread in the contact zone where Tertiary granite intrudes andesites, greenstones and metasediments. The placers are river and bench gravels that yield abundant gold and platinum. In some placers the Au/Pt ratio is 100:1, in others 1:1 and in still others 1:3. Numerous other districts in Colombia also yield gold and platinum mainly from placer deposits, but some districts also contain lode gold deposits. There is a good summary of these deposits in the book by Emmons (1937) and in the paper by Meyer (1941).

The deep leads of Victoria, Australia. Alluvial gold was discovered in Victoria at Clunes in March 1850, and there followed in 1851 the great rush that covered most of the state. The first workings were in the present streams and at the heads and shallow tributaries of the deep leads. By deep leads are meant, according to the legal definition of the Mining Development Act of Victoria, 1896 "any water-course or gutter below the surface of the earth containing alluvial deposits, at depth of not less than 100 feet from such surface."

The bedrock of the goldfields of Victoria is tightly folded Ordovician and Silurian shales, slates, greywackes and sandstones intruded by granitic rocks probably of Devonian age. The gold deposits are quartz saddle reefs interbedded veins and crosscutting veins containing native gold, pyrite, arsenopyrite and a few other sulphides. The principal mining areas, and the sites of many of the deep leads, are Stawell, Glenorchy, Ararat, Moyston, Raglan, Avoca Valley, Ballarat, Bendigo, Daylesford, Castlemaine, Clunes, Malmsbury, Rutherglen and many others.

The Paleozoic rocks and their contained gold deposits were deeply weathered and eroded, and the debris deposited in old river channels mainly during Tertiary time according to the fossil evidence. The deep leads so formed were deposited by rivers trending north or south from a watershed that extended from east to west across the country, coinciding in places with the great dividing range of Victoria. There followed in late Tertiary time further infilling by alluvium, and in places where volcanism was active the valleys were capped by basalt.

The deep leads of Victoria are described in great detail by Hunter (1909), who classifies them as alluvium and basaltic covered deep leads. Their nature is shown in Figure 86. Some of the placers lie close to the original veins in weathered debris and appear to be buried eluvial deposits. In places recent streams have cut down through alluvium and basalt to expose the deep leads. Where this occurs the downstream gravels of the recent streams may be highly auriferous (Fig. 75).

The deep leads are composed mainly of disintegrated country rock, quartz, heavy minerals, flour gold, and nuggets and slugs of the metal. The width of the pay streaks in the channels varies from 100 to 1000 ft or more. The grade varied from 20 to 65 oz Au/running foot in the richer parts. Recent work on the deep lodes of Victoria and a general bibliography of the deposits is given by Bowen and Whiting (*in* Knight, 1975).

Lena, Aldan and Amur drainage systems, Siberia, U.S.S.R. Gold placers are widespread in Siberia. Many are now largely exhausted, but some in the Lena, Aldan, Amur and other drainage systems are still productive and are the largest river placers known. Production from these placers probably exceeds 40 million ounces of gold since their discovery in 1829. Descriptions of the placers of Siberia are given by De Batz (1899), Maclaren (1908), Mushketov (1930), Obroutchev and Guérassimov (1929), Shakhov (1969), Kartashov (1971), Borodaevskaya and Rozhkov (1974) and numerous others (*see* the Selected bibliography).

The placers of Siberia occur mainly near the headwaters of the Ob, Yenisey, Lena, Aldan, Kolyma, Amgun and Amur rivers or near the headwaters of tributaries to these great systems (Fig. 87). Nearly all are in deeply dissected terrains marked by ranges of low hills and an irregular network of streams. They owe their origin to the weathering and erosion of uplifted zones of considerable extent that are marked by gold-bearing deposits of many types in rocks of both sedimentary and volcanic origin. Most placers in Siberia carry one pay streak on or near the bedrock that commonly varies in width from 100 to 1000 ft or more and ranges in thickness from 3 to 25 ft. The grade varies widely, the placers of western Siberia being leaner than in the eastern part of the region. The Yenisey placers are said to have ranged in value from 0.02 to 0.05 oz Au/yd^3; those in east Transbaikal averaged about 0.10 oz Au/yd^3. The Lena placers are much richer in places, and

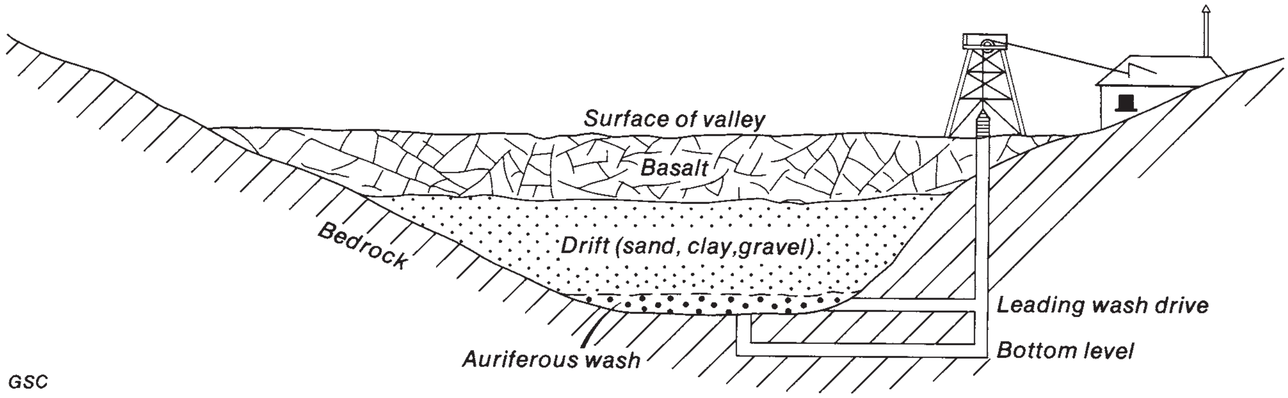

Figure 86. Diagrammatic section showing the nature of occurrence of the 'deep leads' of Victoria, Australia (after Hunter, 1909).

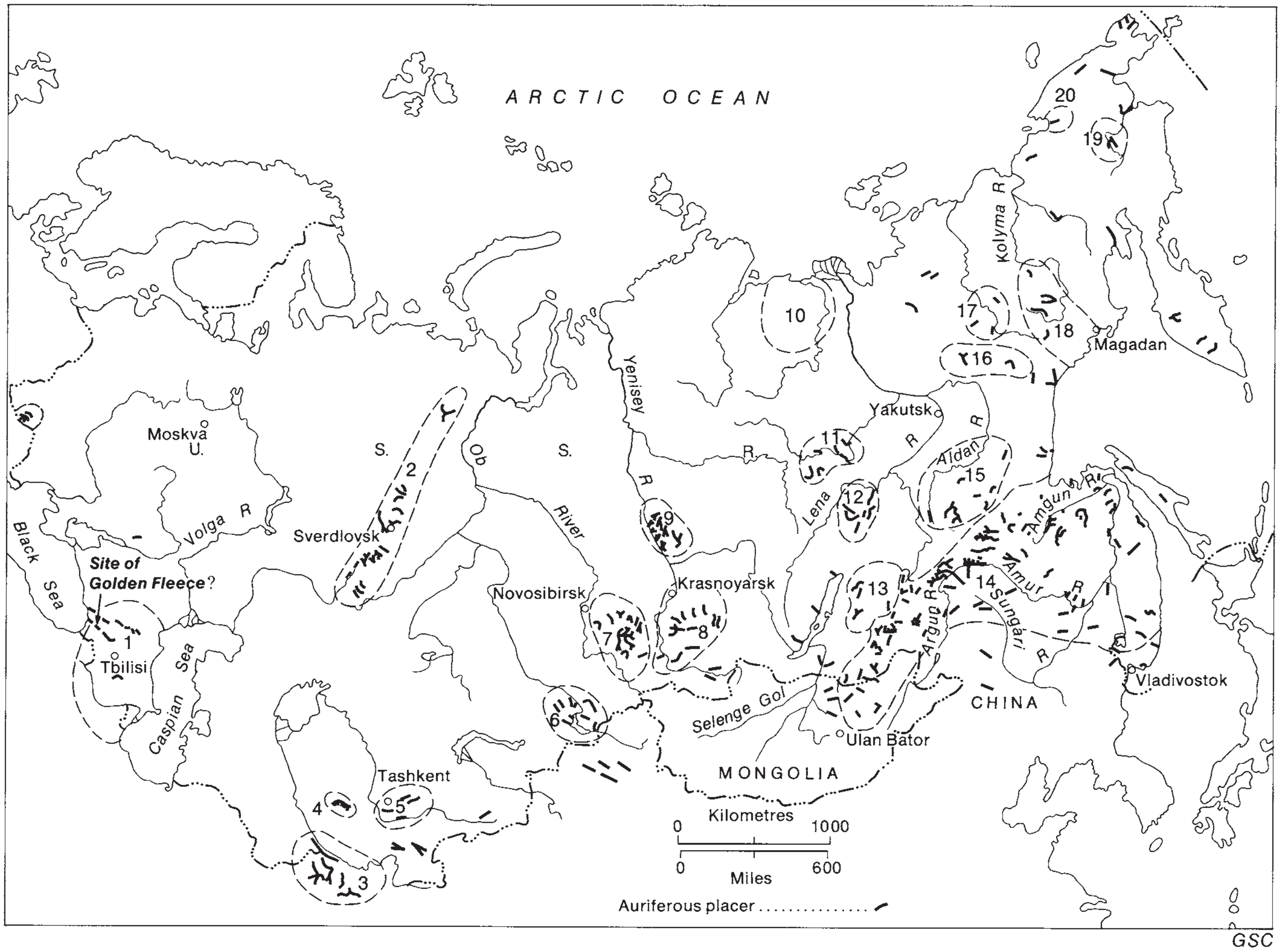

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Figure 87. Map showing the general distribution of the principal auriferous placer districts in U.S.S.R., Mongolia and northern China (Manchuria) (compiled from various sources). Many of the placers shown are exhausted, others are small and probably have produced only limited amounts of gold. Most of the gold production from placers in U.S.S.R. now comes from eastern Siberia.

they frequently carry up to three or more stacked pay streaks.

Most of the placers of Siberia are of late Tertiary and Quaternary age. Many are in the permafrost zone, and a number contain remains of the wooly mammoth (*Elephas primigenius*) and other animals. Some 20 000 wooly mammoths are said to have been found in the placers, a number with the fleshy parts of the bodies intact, a feature suggestive of a catastrophic onset of the frigid climate of the glacial period.

The bedrocks of the Lena placer district are mainly highly folded and faulted crystalline and metamorphic rocks of Precambrian (mainly Proterozoic) and Cambrian age. They comprise mainly sediments such as slates, greywackes, quartzites, phyllites and derived quartz-mica schists and gneisses intruded by quartz-feldspar porphyries and small granitic intrusions, all enclosing quartz veins and stringers of low gold tenor and auriferous pyrite impregnations (Buryak, 1967*a,c*; Polikarpochkin, 1973). Mushketov (1930) stated that the placers of the Lena are located principally in valleys, rich in pyrite impregnations, that are cut into the Precambrian. He also evidently believed that the gold in the preglacial gravels was derived from these pyritic bodies and was chemically precipitated from groundwaters flowing beneath the drift in postglacial times. Research carried out by Sementchenko and others on the pyrite of the Lena placers, which was mentioned by Maclaren (1908), shows this mineral to be rich in gold. This has led to the general conclusion by a number of investigators that the alluvial gold came from the pyrite in the schists of the country rock.

The general topography of the Lena placer district is that of a deeply dissected terrain with low hills and an irregular network of streams. The placers occur mainly in the basins of the Bodaibo, Vacha, Juia and Khomolkho rivers and are of three types: (1) deep alluvial preglacial gravels in old river channels and on benches buried deeply by glacial and interglacial deposits; (2) relatively shallow interglacial gravels in old river valleys; and (3) surface and near surface modern alluvial sands and gravels.

The first are of prime economic importance, the second of some importance, and the third are spotty and lean. The pay streaks of the preglacial placers are a few to several feet thick and wide, 100 to 1000 ft or more, generally much wider than the present river channels. The second and third types of placers were apparently derived from the preglacial gravels. The gold in the preglacial channels is nuggety; some is angular, some crystallized (octahedra and cubes) some rough, and some is well worn. The fineness ranges from 810 to 930, with an average of about 900 according to the old and some of the new records. The average grade seems to be about 6 ppm or 0.17 oz Au/ton of gravel. The normal heavy minerals are magnetite, ilmenite, pyrite, arsenopyrite, native copper, galena, native bismuth, garnet, rutile, tourmaline, zircon, etc.

The extensive placers of the Bodaibo River, a right tributary of the Vitim River, are typical of the Lena drainage system. Most of the gold in these placers is thought to have originated from wide and extensive zones of slightly auriferous quartz veins and sulphide impregnations. Eight benches (terraces) varying in width from 20 to 250 m above the bedrock notch or bottom (thalweg) have been recognized in the Bodaibo Valley. The oldest complex of alluvial deposits in the bottom and succeeding five benches is represented by extensively decomposed and weathered, bright yellowish brown and greyish brown, clayey pebble and boulder beds and gravels. These are considered to be of Early and Middle Quaternary age and are overlain by morainal boulder clay assigned to the maximal Samarov glacial period. The youngest complex comprises grey and yellowish grey, sandy and clayey gravels, boulder beds and sands of the upper three benches and the bottom (thalweg) of the present Bodaibo River. The gravels and sands on the benches are regarded as of lacustrine and fluvial origin and are assigned to the Kazantsev interglacial period; the latest alluvium is considered to be of Late Quaternary and Recent age.

The richest placers of the Bodaibo are those on the second bench above the bottom, but the first bench and others below the glacial clay have also been productive, especially the fourth bench, which is the most extensive. The dimensions of individual pay streaks on the benches vary greatly being from 10 to 200 m wide and up to several hundred metres in length. Most average about 1 m in thickness, but some are up to 5 m thick. The depth of overburden to the deepest pay streaks averages 25 m but may be up to 150 m in some sections. In places gold penetrates into the bedrock (mainly sandstones and shales) to depths of 1 m or more. Most of the gold grains in the Bodaibo placers average about 3mm in size. Nuggets are particularly common, some weighing several kilograms or more. This type of nuggety gold usually has a high fineness, 870 to 930. A second variety of gold, occurring locally in the western part of the basin, has complex shapes, is spongy, drusy and dendritic, and the grains are relatively low in fineness, 730 to 820.

The Amur River (Chinese, Hei-lung Chiang) forms part of the frontier between the Soviet Union and the People's Republic of China. It rises on the northern border of northwest China and Inner Mongolia, flows generally eastward and empties into Tatarskiy Strait separating Siberia from Sakhalin Island. Along its course the Amur and its tributaries, the Zeya, Bureya, Sungari, Ussuri and Amgun, traverse a vast territory with rocks ranging in age from Precambrian to Recent. The topography of this enormous drainage system ranges from mountainous to subdued deeply weathered to lowland. The mineral deposits in the area range from auriferous quartz veins to auriferous sulphide bodies of many types to mercury- and tin-bearing deposits.

The alluvial placers of the Amur drainage system include creek, gulch, river and bench types. Some are worked in a small way; others are extensively dredged. In total the placers of the Amur provide a large proportion of the gold production of the Soviet Union. The details of the placers are much the same as those described for the Lena system and need not be repeated at any length.

Permafrost is comparatively rare in the maritime placer areas but becomes more persistent in the mid-reaches and head waters of the Amur and its tributaries. Frozen ground is uncommon along the courses of the main rivers, making dredging especially favourable. In most of the placer areas the alluvium is auriferous throughout with particularly rich sections at or near or in the first few feet of bedrock. In most sections the ratio of the gold-bearing alluvium to the overburden (turf) averages about 6:1. The alluvium, which comprises both sands and gravels, ranges from less than 0.04 oz Au/ton to values greater than 0.15 oz Au/ton. The average gold content of the valley gravels along the larger rivers appears to be about 0.02 oz/ton and the average of the alluvium for most of the placer districts is 0.05 oz/ton.

China and Mongolia. Much of the modern and ancient gold production of China has come from placers of both eluvial and alluvial origin (Juan, 1946). The bedrocks of China are chiefly Precambrian metasediments and volcanics, Paleozoic and Mesozoic sedimentary rocks and smaller areas of Tertiary sediments and volcanics. Vast areas of the country are covered by Pleistocene and Recent alluvium. Gold deposits comprise principally quartz veins and stockworks, silicified pyritic bodies, polymetallic lodes in limestone and auriferous conglomerates, the first three types being related to granitic intrusion and metamorphic events of Proterozoic (Algonkian), late Paleozoic and Cretaceous-Tertiary age (Emmons, 1937; Juan, 1946).

Placers are associated with many of the auriferous deposits mentioned above. These include ancient (Tertiary?) valley gravels, Pleistocene and Recent high level (terrace) gravels, Recent stream gravels and marine placers. The last are relatively insignificant. The principal producing rivers and streams are in Shantung, Kiangsu, Fukien, Chihli, Hupeh (Han and Yangtze rivers), Hunan, Kwangsi, Szechuan, Kansu, Tsinghai, Yunnan and Heilungkiang, Kirin and other regions of Manchuria. The Manchurian placers seem to be the most productive, and they are said to have large reserves. The important placer drainage systems include those of the Sungari, Tumen Ho, Nonni, Amur and Yalu rivers (Fig. 87). Some 200 000 oz of gold per annum are won from these placers.

Alluvial gold placers are widespread in Mongolia particularly in the area north of Ulan Bator near the U.S.S.R. border. There, auriferous gravels have long been worked along the Selenge Gol, Orhon Gol, Tula Gol, Hereleng Gol and their tributaries. The source of the gold is mainly scattered quartz veins in various schists and gneisses intruded by granitic stocks and dykes. These placers and deposits are on the southwestern extension of those in the Transbaikal region of U.S.S.R.

Modern beach placers

Modern beach placers carrying economic amounts of gold are relatively rare. The classic example is the beach placers at Nome in the Seward Peninsula, Alaska. Other examples, all now exhausted are known along the Oregon and California coasts, in Nova Scotia, British Columbia, along some of the beaches in Chile, along the coasts of Westland and Southland in New Zealand and elsewhere. Those at Nome demonstrate most of the features of gold-bearing beach placers.

The beach placers at Nome and the geology of the area are described in detail in the publications by Collier *et al.* (1908), Smith (1908), Gibson (1911), Moffit (1913), Hummel (1962*a,b*) and Cobb (1973). Briefly, the bedrock in the vicinity of Nome is composed of highly folded and faulted metamorphic rocks, mainly of Paleozoic age, consisting of various sediments now largely schists, graphitic quartzites, phyllites, limestones and graphitic slates, all cut in places by granitic rocks and greenstones. Veins and small lenticular masses of quartz and calcite are widely distributed in all of the metamorphic rocks but most abundantly in the schists of the Nome Group near the localities rich in placer gold. Most of the veins, especially the larger ones that crosscut the foliation, carry free gold and sulphides. Silver-lead veins are also known from Seward Peninsula, and there are quartz veins bearing cassiterite and a little gold in the far western part (Moffit, 1913; Cathcart, 1922).

The Nome area is characterized by a crescent-shaped, flat, alluvial coastal plain or tundra that intervenes between the sea and the highlands which rise to 1000 ft or more some 5 mi inland. The alluvium of the coastal plain is predominantly fine, usually sand and sandy clay, with some coarser gravel layers and frequent beds of clay. Most of it is slightly auriferous. These sediments represent late Tertiary and Quaternary deltaic deposits laid down in the sea by streams and rivers bringing material from the auriferous highlands. The gravels and sands are up to 100 ft or more in thickness in places and are covered with muck to varying depths. Inland, the alluvial deposits are river, stream and lake gravels and sands. The Nome area was extensively glaciated during Pleistocene time, and parts are underlain by permafrost.

The placers of the Nome area (Fig. 88) include the following types:

1. *Eluvial placers* mainly on the slopes of hills represented by those on Rock Creek, Pioneer Gulch, Boer Creek and Nekula Gulch: The gold is coarse and angular and occurs on or in the upper part of disintegrated schists. These placers have been worked in a small way.
2. *Gulch, creek, stream* and *river placers* represented by those in the Snake River basin, Dry Creek and Newton Gulch, Nome River basin, Hastings Creek, Fred Gulch, Hazel Creek and others: These have been extensively worked; characteristic heavy minerals are scheelite, bismuth, pyrite, arsenopyrite, magnetite, ilmenite and limonite. The gold is fine to coarse grained, and nuggets are common.
3. *High-bench placers* are stream placers laid down in former drainage systems. Several have been worked mainly at the head of Dexter Creek in the low saddles in the watershed between the Snake and Nome rivers.
4. *Gravel-plain placers* are scattered and do not occur as well defined concentrations but as irregular accumulations disseminated through the gravels. Most are small and lean. Their origin is uncertain. Most appear to be related to river deposits.
5. *Beach placers* include modern, buried and raised types. They are the subject of the discussion that follows.

Work done up to 1970 indicated that there were 12 recognizable beaches in the Nome tundra, including offshore, modern, submarine, second, intermediate, Monroeville, third and fourth as indicated in Figure 89. The beaches represent successive periods of Quaternary and older coastal uplift that extended over a considerable length of time.

On the present beach the gold was concentrated on clay or micaceous sandy false bottoms. The pay streaks were 250 to 300 ft wide and about 2 to 18 in. thick above the clay beds, the latter being some 45 ft above bedrock. The pay streaks were a series of discontinuous stratified lenses containing essentially quartz and granite sand and pebbles with schist and limestone shingle in which gold was plentiful and associated with magnetite, garnet, limonite, hematite, ilmenite, scheelite and pyrite. Most of the gold was fine grained and well worn.

The second beach lies about ½ mi inland and some 40 ft above sea level. The gold streak, some 6 in. thick and 25 to 100 ft wide, lies on a false bottom of sandy and micaceous sediment and is buried under 15 ft or so of overburden. Most of the gold was a bright yellow colour, flaky and fine grained; some was about the size of gourd seeds. The pay streak in places ran up to 0.1 oz/pan.

The submarine beach lies almost directly under the second beach and some 56 ft lower. Where the bedrock is high the pay streak lies on it, elsewhere it lies on a false bottom of clay, sand and gravel at an elevation equal to that of the top of the rises in the bedrock. The pay streak lies under 60 ft or so of overburden and is 1 ft to less than 3 ft in thickness and from 300 to 400 ft wide. The gold is uniformly distributed through it, and the heavy minerals are somewhat different than those of other beaches. They include abundant pyrite and arsenopyrite with garnets, magnetite and ilmenite. The gold was bright yellow and fairly coarse; the grade of the pay streak ranged from 0.2 to 0.5 oz Au/yd^3.

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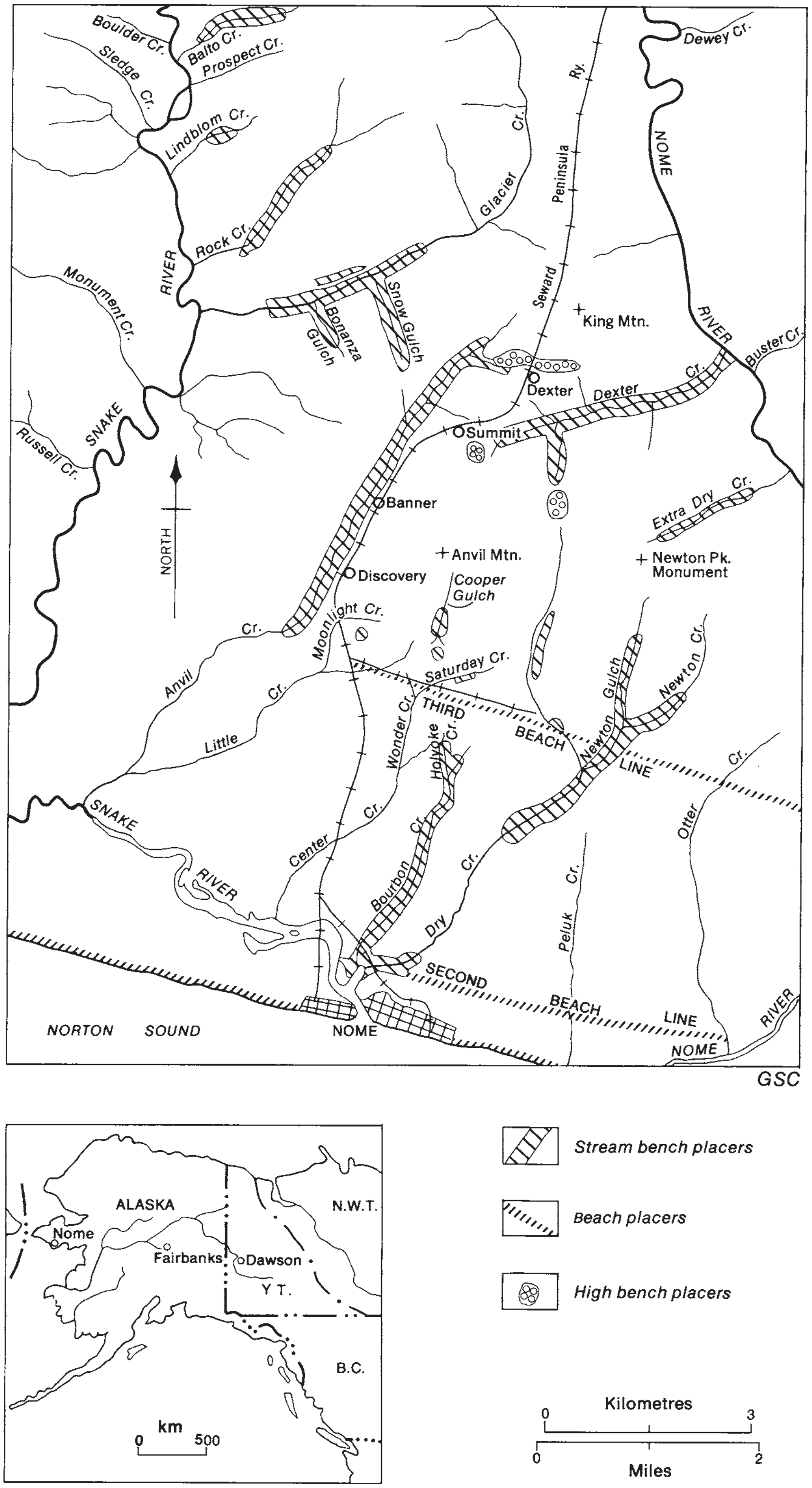

Figure 88. Map showing the distribution of the various types of auriferous placers in the Nome district, Alaska (after Collier *et al.*, 1908).

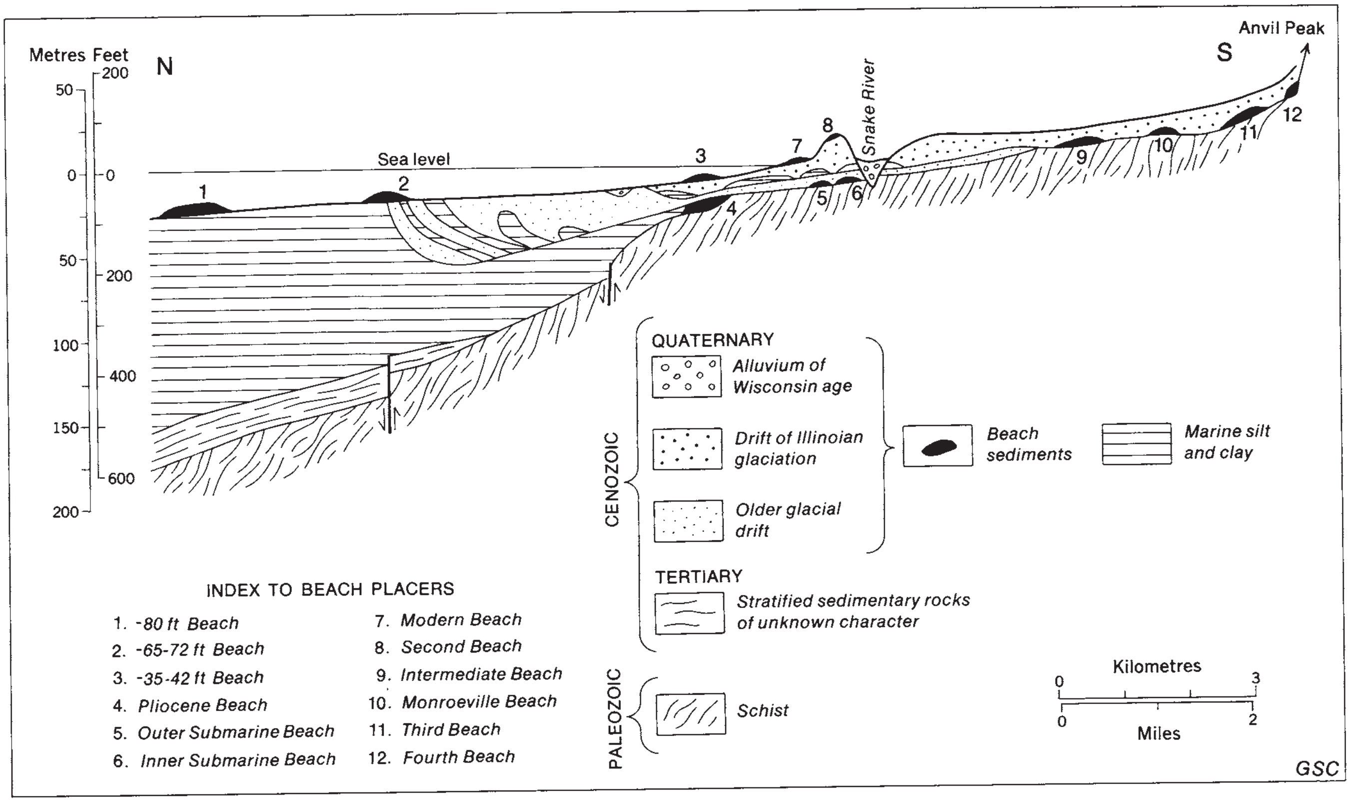

Figure 89. Geological section across the coastal plain area at Nome, Alaska showing the various auriferous beaches (after Nelson and Hopkins, 1972).

The intermediate beach lies about 1¾ mi inland and rests on bedrock some 20 ft above sea level. The pay streak is 1 to 3 ft thick, 400 to 600 ft wide, lies on or in the first foot or so of the bedrock, and the gold tenor is 0.25 to 0.75 oz Au/yd^3. The gold is bright yellow and fine grained, accompanied by abundant pyrite, arsenopyrite, magnetite and ilmenite. A characteristic feature of this beach is the presence of abundant mollusk shells, hence the name 'Clamshell Beach'.

The third beach, which is the richest of all, lies 70 ft above sea level and much of it rests on bedrock. The pay streak is mainly on the bedrock, 5 to 12 ft thick, 100 to 600 ft wide and covered by 20 to 120 ft of overburden. The gold was fine grained, but some nuggets were also found. Some parts of the pay streak were fabulously rich, in places 1000 oz/yd^3 or more. Much of the gravel of the pay streak ran 0.25 oz/yd^3. Gibson (1911) remarks that pay streaks in naturally thawed areas (thaliks) are not nearly as rich as those in the areas of permafrost. The reason for this he says is unclear. In Yukon there are indications of a similar phenomena in places. The writer thinks that the reason is due to leaching of the gold from these thawed areas by the groundwater. That gold (and silver) is capable of migrating in the permafrost is beyond doubt as shown by the writer (Boyle, 1951,1965*a*); under warmer conditions where groundwaters are moving, the effect is reinforced with time.

The Monroeville beach is considerably different than the others. The gravel is coarser, and the gold is much coarser than in the other pay streaks and is mainly in the shattered bedrock. There is also little garnet but plenty of pyrite and arsenopyrite. The pay streak is low grade and 300 to 500 ft wide being composed of 1 ft of gravel and 2 to 3 ft of bedrock. It is overlain by 50 ft or so of overburden and is 33 ft above sea level.

The fourth beach marks an ancient shoreline, but apparently there is no rich pay streak associated with this beach.

Extensive areas of the Nome beaches have been dredged after thawing of the gravels.

Recent work (since 1970) in the Nome area described by Nelson and Hopkins (1972) has revealed the presence of other beaches offshore and on bedrock as shown in Figure 89. In addition gold has been found over a widespread area in the sediments of the northern Bering Sea. (*See* further under the section on glacial and postglacial placers.)

The origin of the auriferous Nome beaches is of interest. Originally the gravels were of coastal plain deltaic origin and relatively lean in gold. During coastal uplift each successive beach has seen the winnowing and concentration of gold from the gravel plains by wave action. There may also have been contributions of gold by streams debouching their sedimentary load in the shallows along the beaches.

Small marine beach placers have been worked along the coasts of Oregon and northern California. Those in Oregon have been described by Pardee (1934). Recent work on the gold content of sediments along the coasts of Oregon and California by Clifton (1968) and Moore and Silver (1968) revealed some anomalous areas requiring further investigation.

Some of the black sands of Graham Island, Queen Charlotte Islands, British Columbia are auriferous. These occur along the beaches and originated from the reworking of extensive morainic deposits by wave and wind action (Mandy, 1934). The sands consist essentially of magnetite, garnet, epidote and olivine. The gold occurs as fine colours and is said to be present in amounts up to ⅓ oz/yd^3 or more in some of the magnetite-rich lenses. Overall, however, the beach sands are characteristically low grade.

In Nova Scotia small gold placers, mostly of academic interest, occur along the beaches of the Atlantic where the gold-bearing Meguma Group rocks are eroded by waves. One occurrence at the Ovens contained some 2000 oz of gold as small flakes and nuggets in the sand, the metal apparently being derived from nearby lean gold-bearing quartz veins and auriferous pyrite- and arsenopyrite-bearing slate and greywacke (Malcolm and Faribault, 1929). Offshore there may be placers of similar origin and these could be relatively rich and large where the Meguma Group rocks have been extensively eroded. These are discussed subsequently.

In Chile beach sands occur at Cucao and at Carelmapu, the latter in southern Chile. Some of these placers were very rich in places.

Auriferous beach placers of Recent age have a widespread distribution along the coastline of Westland and Nelson, New Zealand. They have been sluiced, dredged and worked as deep leads extensively in the past at Bruce Bay, Gillespies Beach, Addisons Flat, Okarito, Saltwater Beach, Barrytown, Charleston and elsewhere. Three types of beach placers can be recognized: those developed along the present strandline; those developed along former strandlines that are now submerged; and those developed along former strandlines that are elevated and now appear as raised terraces (beaches) inland from the coast. Well sorted and rounded pebble gravels with sandy intervals constitute most of the placer materials; some are cemented by ferruginous oxides, mainly limonite. The gold is extremely fine grained and is generally accompanied by ilmenite, magnetite, garnet, zircon, monazite, rutile, tourmaline, hornblende and epidote. Some scheelite and thorite occurred in the more southern placers. The thickness of the beach gravels ranges widely; some are up to 50 ft and contain stacked gold streaks that tend to parallel the present coastline. The source of their gold would appear to be multiple depending on their location, including auriferous Pleistocene gravels, older auriferous Tertiary and Cretaceous conglomerates, Precambrian(?) Greenland and Waiuta rocks and their gold-bearing lodes and the Alpine Schists. In Westland and Nelson these placers and beachsands represent a large reserve of blacksand from which gold could be won as a byproduct. Their details and locations are discussed by Williams (1974).

Glacial and postglacial placers

Glaciation generally destroys preexisting placers and scatters the gold far and wide. Few glacial deposits such as till sheets, kames, moraines, eskers, terraces, stream gravels and outwash deposits contain concentrations of gold. However, a few of the water-sorted materials associated with glaciers of both mountain and continental type may contain small placer concentrations. The placers of the Chaudière basin, Quebec described in some detail above probably owe their origin at least in part to concentration in glacial sands. Similarly, some of those in the Cariboo and in other parts of British Columbia, Yukon and Alaska commonly have a glacial sand and gravel component, and some of the gold has been reworked from older gravels into pay streaks, lean in most places. Similar conditions seem to have prevailed in the placer districts of Siberia and northern Europe.

It should be stressed that glaciation does not preclude the presence of gold placers. The existence of the Cariboo, Chaudière, Nome, Aldan, Lena and many other placers in regions that have been extensively glaciated should dispel any thought that glaciation is inimical to the preservation of Tertiary and Quaternary placers and the formation of new placers from these during glacial periods. In this respect it is worthwhile considering that deep Tertiary(?) or Pleistocene valleys now buried under great thicknesses of glacial clay and till may contain valuable placers in Canada, Europe, Asia and elsewhere.

Postglacial concentrations of gold in the gravels and sands of river systems and in oceanic sediments are common in Canada and many other countries. A few examples will serve to illustrate the nature of these placers.

Economic gold placers of glacial derivation have been worked extensively in Westland and Nelson provinces, New Zealand. In northern Westland these placers are floored or bottomed by the ‘Blue Bottom’, an upper Miocene formation of marine clay with glauconite. It is nonauriferous and is succeeded by an early Pleistocene formation known as the ‘Old Man Gravels’, consisting of loosely consolidated, rusty well rounded pebbles of greywacke, granite and schist. This formation has been recognized from the Grey River in the north south to the Mikonui River at Ross; it is slightly auriferous, but the source of the gold is uncertain, being probably partly derived from the Precambrian(?) Greenland and Waiuta rocks, which contain auriferous lodes and partly from the geosynclinal schists east of the Alpine Fault. The Old Man Gravels have been worked at several places but apparently seldom with profitable results. Their chief importance is that they were probably extensively reworked and are an important source of gold for the younger Pleistocene and Recent placers.

Moraines and glaciofluvial deposits were laid down during Pleistocene time over large areas in Westland Province by piedmont and valley glaciers that descended from the Alps to the present Westland coastline. The deposits of interest, many of which are auriferous and apparently of several generations, include esker, kame, stream and outwash plain gravels and sands that extend from north of Reefton to Ross. They have been extensively worked at Stafford, Goldsborough, Kumara, Greenstone, Dunganville, Stillwater Valley, Notown, Red Jack’s and elsewhere. The auriferous materials constitute gravels and sands laid down below the glaciers and winnowed from their frontal moraines, mainly the latter. The source of the constituents of the gravels and sands and the gold is varied, some was derived from the Precambrian Greenland and Waiuta greywackes and their auriferous lodes, some from the Alpine Schists and some from the reworking of older auriferous early Pleistocene, Tertiary and Cretaceous conglomerates and sands. The gold in most of the glacial gravels is flaky, fine grained with an occasional small nugget. In most areas the quality of gold in the gravels was noted to diminish progressively with distance from the ancient ice edges. The Pleistocene gravels have, however, been extensively reworked yielding Quaternary and Recent placers along many of the rivers, streams and beaches of Westland from the Buller River south to the Mikonui River. In the past these have also been extensively sluiced and are largely exhausted, but one dredge still operates on gravels in the Taramakau River northwest of Kumara, producing some 1000 oz Au/month. Details of the auriferous Pleistocene and Recent gravels are given by Park (1908), Morgan (1908) and Williams (1974).

Gold has been known in the North Saskatchewan River since about 1859 and has been won by hand methods and dredging (Tyrrell, 1915). Gold is also present in a number of other rivers in western Canada including the Red Deer, Athabasca and McLeod (Fig. 79). Most of the gold in the North Saskatchewan River is present as very minute flakes and pellets in coarse gravel on the top few inches or few feet of the bars in the river all the way from Rocky Mountain House to Prince Albert, a distance of some 500 mi or more. The richest parts begin near Goose encampment, where the big coal seam at the top of the Cretaceous Edmonton Formation crosses the river, continue past Edmonton and cease in the vicinity of Beaver Lake Creek. Throughout the whole of this distance the coal-bearing Edmonton Formation forms the banks of the North Saskatchewan Valley. Tyrrell says that some 28 000 oz of gold have been washed from the river. He also believes that a small amount of platinum is also associated with the gold.

The auriferous pay streaks in the North Saskatchewan River are certainly of postglacial origin. The source of the gold, however, is problematical. Some have thought that the gold originated in undiscovered lodes in the Rockies; others have considered that the metal was washed out of the glacial till, clay, sand and gravel spread over the foothills and prairie; and still others think the gold came from the Tertiary sedimentary formations or from the Cretaceous rocks of the Edmonton Formation. Tyrrell (1915) was among the advocates of a source in the Edmonton Formation, since he found traces of gold in the coal ashes and clinkers resulting from the in situ burning of the seam. It seems probable that the coal-bearing parts of the Edmonton Formation are indeed the source of the gold since pyrite is common in these rocks, and pyrite in coal is commonly slightly auriferous. (*See also* the section on gold in coal in Chapter II.)

The Vermilion River in Ontario has long been known to contain gold. In the writer's opinion the Vikings may have found gold there, but the recent discovery of the gold-bearing sands was made in 1896. Meyn (1970) summarizes the available information on the occurrence of gold in the river basin. Earlier reports were written by Gracey (1898), Coleman (1901) and Prest (1949). The gold is very fine grained and disseminated throughout the sands and gravels. There appear to be no pay streaks, although some of the gravels are richer than others. Occasionally one can recover a piece of gold the size of a pin head in places, but according to all reports nuggets are rare. The average value of most of these gravels is about 0.005 oz Au/yd^3 or less, although some have been reported to run up to 0.02 oz Au/yd^3. The source of the gold is uncertain. Coleman (1901) thought that it probably came from the auriferous deposits in the Huronian rocks to the north and northeast; others have considered the Porcupine and Shining Tree areas as the source. Probably much of the gold has come from the winnowing of glacial till, gravel and sand by postglacial and modern streams and rivers in the Vermilion River system. If this is so, the gold has a widespread origin, coming from rocks and deposits of many types.

Other rivers and areas where placer gold can be panned from reworked glacial materials in Ontario include Wanapitei River, Meteor Lake, Lake Manitou, Savant Lake, Grassy River (south of Timmins) and various glacial sands in Munro, McCool, Montrose, Timmins and other townships. In Northwest Territories there are numerous eskers, outwash sand deposits and reworked glacial sands that yield a colour or two of gold with persistent panning. None of these are economic.

Gold concentrations in modern river sands and gravels, similar to those just described, occur in many of the river systems of the world of which the most celebrated must be the Rhine, immortalized in Wagner's prelude "Das Rheingold" to the great opera "Der Ring des Nibelungen".

Gold concentrations in ocean sediments on continental shelves occur in various parts of the world. Most are low grade and up to the present have not been mined. Numerous examples of these concentrations can be cited. Two offshore concentrations from the Ovens in Nova Scotia have been described by Libby (1969). Here, the gold appears to occur in ancient buried stream channels, although some probably also occurs in old beach deposits. The tenor of the sands and gravels is said to range from a few cents per cubic yard to more than four dollars per cubic yard (0.001 to 0.11 oz/yd^3). The volume of gravel available in one deposit is 6 million and in the other 36 million yd^3.

Pilkey and Bornhold (1970) examined the heavy mineral fractions of sediments from the Carolina continental margin United States, offshore from the deposits in the Piedmont and Blue Ridge gold provinces. Most of the measurable concentrations of gold were very low (0.7 to 7.0 ppb) in the heavy mineral fractions and restricted to the general vicinity of Cape Lookout and northward.

A number of submarine areas in Alaska have been investigated for detrital gold. Reimnitz *et al.* (1970) found no gold in the bottom mud of Nuka Bay, a fiord system along the northern Gulf of Alaska fed by numerous streams carrying gold. A small amount of gold was detected in two samples of relict gravel and in relatively unsorted coarse material dumped into the head of the fiord by glacier. The investigators concluded that the gold apparently moves with the coarse fraction of the sediment supply and is retained in deltas and moraines where there is little chance of finding an economic concentration.

In the northern Bering Sea, Nelson and Hopkins (1972) found that glaciers had moved auriferous debris as much as 5 km beyond the present shoreline of Seward Peninsula and nearly to the centre of the Chirikov Basin from Siberia's Chukotka Peninsula. The richest concentrations (920 ppb) and coarsest particles (1 mm or larger) of gold were found in seafloor relict gravels that mantle glacial drift lobes in the Nome nearshore region and in gravel patches over bedrock in the Sledge Island area. These bodies of relict gravel are thought to have formed during transgression and regression of the shoreline when eustatic changes of sea level occurred in

Pleistocene time. Except along the present shoreline, Holocene (Recent) sands and muds throughout most of the southern Bering Sea were generally found to contain only sparse fine gold flakes (0.25 mm in diameter or smaller). The total background gold content of Chirikov Basin sediments is not well defined, but analysis of several whole samples suggests an average of about 10 ppb.

Fossil gold placers

Fossil gold placers may be of residual, alluvial or aeolian origin and include ancient eluvial, alluvial fan, piedmont fan, talus, gulch, creek, stream, river flat and channel, deltaic, beach, coastal plain and marine types. On uniformitarian principles we assume that these deposits originated in a manner similar to that described above for each of the modern types. Their detailed history, however, may be complex as pointed out by Fayzullin (1968). There may have been a number of intermediate collectors of gold between its primary source and its final site of deposition. This is especially true where multiple erosion cycles are a feature of the geological history of a district. Furthermore, this recycling process may partly explain why the gold in fossil placers is generally much finer grained than that which we commonly see in modern (first cycle) placers near the source of the gold. Most fossil gold placers are in transgressive rock sequences and commonly occur on or near ancient weathered and eroded surfaces, i.e., unconformities, although some may be stratigraphically higher than the basal beds at unconformities. In age fossil gold placers range from Precambrian to Tertiary. Two general types can be recognized – one type is extensively lithified and contains much pyrite and often other sulphides, a few deposits of this type contain hematite (or ilmenite) as the principal iron mineral; another type is only moderately to weakly lithified and contains little pyrite and other sulphides but often plenty of iron oxides (limonite, hematite). To the first belongs the quartz-pebble conglomerate deposits, the largest and most productive gold placers known; the second category includes many gold-bearing sandstones, quartzites and conglomerates throughout the world. No attempt will be made here to describe any of the latter type in any detail, but some specific examples will be briefly mentioned.

Auriferous, pyritic quartz-pebble conglomerates are especially characteristic of the Precambrian and are generally of Lower Proterozoic age. They most commonly lie immediately above the Archean-Proterozoic boundary as emphasized by Derry (1961) and seem to have derived most of their gold from auriferous deposits in Archean rocks. The most productive of these deposits have been described above, the references to other occurrences of a similar type throughout the western world are given there. In U.S.S.R. there are numerous pyritic quartz-pebble conglomerates of Precambrian age, but so far as is now known none of these are productive of gold. Most apparently contain only from 0.1 to 1 ppm Ag. They include occurrences in Karelia, Krivoy Rog, Kursk magnetic anomaly, Voronez syneclise, in the district west of Lake Baikal, Vitim-Patom Highlands, the eastern and western portions of the Aldan Shield, around the rim of the Anabar Shield and elsewhere. These conglomerates and methods of their study are the subject of monographs by Smirnov (1969) and Ivensen *et al.* (1969).

Pyritic quartz-pebble conglomerates are not restricted solely to the Precambrian. On the contrary, occurrences of this kind are known in Paleozoic and Mesozoic rocks and may also occur in Tertiary rocks. None of the younger occurrences are, however, economic, as far as the writer can ascertain.

The economic quartz-pebble conglomerates have had a long and complex chemical and metamorphic history, and their origin is controversial. It is suggested in the last part of this chapter that these deposits are essentially placers in which the various elements, including gold, have been extensively redistributed.

The second type of fossil placer occurs in sandstones, conglomerates and quartzites that are marked by the presence of little pyrite but often contain much hematite or limonite. This type is usually only moderately lithified, and the gold is in most cases easily recognized as detrital. There are a number of occurrences of these types of placers in Canada.

Near Gays River, Nova Scotia, Carboniferous (Horton Group) conglomerates, consisting of pebbles of slate and quartz in a gritty matrix of quartz, slate particles and iron oxides, overlie auriferous slates and greywackes of the Meguma Group for 4 mi (Malcolm and Faribault, 1929; Stevenson, 1959). The basal beds and the underlying slate, where it is fractured or jointed, are auriferous. The gold, bright and of a deep yellow colour, occurs as thin flakes and small nuggets in the matrix of the conglomerate and in the fractures of the slate. It is associated with considerable amounts of iron oxides in places. The source of the gold appears to be auriferous quartz veins in Meguma rocks to the southeast.

Analyses of the various types of gold-bearing conglomerates are given in Table 70. It will be noted that the manganese and iron contents of some of the facies are relatively high. No systematic correlation could be found between the gold contents and the iron and manganese contents, except that in some places the iron-rich varieties of conglomerates seem to contain a little more gold. Of the other elements only arsenic appears to be higher than normal, being probably concentrated mainly in the iron oxides.

The gold contents of the various facies of the conglomerates are low according to Geological Survey analyses (<10–35 ppb) (<0.0002–0.001 oz Au/ton). Some of the heavy concentrates made from the conglomerates are rich in gold (up to 18.5 ppm; 0.54 oz Au/ton) as well as in elements such as Ag, Ti, Mn, Ba, Cr, V, Ni, Cu, Zr, Ce, Y, Nd, Nb and Th, mostly reflecting the presence of heavy minerals such as magnetite, ilmenite, wad, barite, zircon and monazite.

According to Malcolm and Faribault (1929), 1878 oz of gold were won from 11 877 tons of crushed conglomerate between the years 1873 to 1881. This gives an average of 0.158 oz Au/ton (5.4 ppm).

Pan concentrates from the sediments of streams near the conglomerates are enriched in gold (up to 8.5 ppm). This feature suggests a method of tracing the auriferous conglomerates in drift-covered areas. Careful assessment of the results will be necessary, however, to differentiate gold anomalies due to weathering of the conglomerate from those due to weathering of auriferous deposits in the Meguma rocks.

In New Brunswick Carboniferous conglomerates are slightly auriferous near Nauwigewauk (Ingall, 1893). The conglomerate beds consist of interstratified coarse sandstones

Table 70. Analyses of Carboniferous auriferous conglomerates, Gays River area, Nova Scotia

Constituent	Manganiferous conglomerate	Hematitic conglomerate	Grey conglomerate
		(%)	
SiO_2	73.9	74.2	79.6
Al_2O_3	9.7	10.1	10.0
Fe_2O_3	3.5	3.5	2.5
FeO	0.8	1.6	<0.1
CaO	2.4	2.3	0.3
MgO	0.9	1.1	0.4
Na_2O	0.8	0.5	0.4
K_2O	2.8	2.7	2.6
H_2O (total)	1.6	1.6	1.5
TiO_2	0.29	0.33	0.31
P_2O_5	0.10	0.08	0.08
MnO	1.06	1.00	0.38
CO_2	2.6	2.6	0.2
S	0.13	0.12	<0.02
F	<0.02	0.10	<0.02
Cl	0.08	0.04	<0.02
C	0.16	0.09	nf
$O \equiv$ Cl, F, S	0.07	0.10	0
Total	100.8	101.9	98.3
		(ppm)	
Cu	27	15	33
Ag	0.14	0.12	0.08
Au	<0.01	0.01	<0.01
Sr	76	70	55
Ba	430	310	300
Zn	19	19	16
Cd	<0.6	1.3	1.3
Hg (ppb)	10	23	12
B	143	145	163
Ga	12.8	13.3	13
Tl	<1.0	<1.0	<1.0
Sc	6.1	8.8	8.2
U	0.4	<0.1	1.4
Ge	2.4	2.4	3.1
Sn	3.3	3.3	3.3
Pb	12	12	12
Zr	120	110	109
As	25	13	18
Sb	2	<2	2
Bi	0.6	0.53	<0.50
V	40	37	31
Cr	21	26	25
Mo	1	3	2
W	<2	<2	<2
F	<0.02	0.10	<0.02
Cl	0.08	0.04	<0.02
Co	23	24	18
Ni	28	28	28

Note: nf–not found.

and pebble beds, the pebbles being mainly of quartz, shale and limestone. It is said that the gold is free and very fine and apparently contained in the quartz pebbles that make up part of the conglomerate. The more pebbly beds are said to carry up to 0.2 oz Au/ton.

The Edmonton Formation along the North Saskatchewan River is slightly auriferous as noted in the previous section. Some of the Tertiary rocks overlying the Edmonton Formation may also be slightly auriferous judging from old reports.

The Tertiary (Eocene) conglomerates southwest of the Indian River (McKinnon and Bismark creeks) in the Klondike district of Yukon are slightly auriferous (Fig. 76). These conglomerates are composed of well rounded white quartz pebbles and cobbles and schist particles cemented by fine-grained quartz and schist fragments. A few grains of pyrite occur in places, usually near the base of the series. The conglomerates are not unlike the auriferous 'White Channel Gravels' of the various creeks of the Klondike except that they are more strongly lithified. In gold content the conglomerates are low, but when panned a few fine colours usually appear. Maclean (1914) reports nil or only traces of gold from the old workings; others report from trace to 0.1 oz Au/ton. As far as the writer is aware, little has been done on the conglomerates except some diamond drilling since Maclean's report. Mertie (1940) mentions similar auriferous conglomerates in Alaska south of the Yukon River in a narrow belt that extends from the Internatonal Boundary west-northwest for more than 100 mi.

Elsewhere in the world gold-bearing conglomerates, sandstones and quartzites appear to be relatively common. A few examples will suffice to indicate their nature.

The Paleozoic Deadwood Formation of the Black Hills region of South Dakota has long been known to be auriferous, and parts of the formation (Cambrian Potsdam Formation of Devereux) have been mined (Devereux, 1882; Irving *et al.*, 1904; Connolly, 1927; Norton, 1974). One of the richest auriferous parts of the Deadwood Formation is near the large Homestake gold deposit where the basal conglomerate, breccia and sandy beds rest on Precambrian schists, amphibolites, etc. (Fig. 90). The auriferous conglomerate ('cement ore') is composed mainly of quartz pebbles and boulders, schist shingle and pebbles of hematite (iron-formation) cemented partly by pyrite, oxidized to various iron oxides in the oxidized zone. Pockets of iron oxide or pyritic material in depressions and channels in the underlying Precambrian rocks were especially rich in gold. Some of the gold occurs in well rounded small flattened nuggets on or near the Precambrian bedrock. Another type of gold occurs as films and flakes along schist planes and in fractures and crevices in the Precambrian schistose bedrock to depths of 10 ft or so in places. Small amounts of gold are also present in, or associated with, the pyrite that may have been introduced in Tertiary time. Yet another type of gold occurs some miles distant in quartzites intruded by porphyry dykes of Tertiary age. This gold occurs in the native form in a very fine state of division mainly in cavities lined with quartz crystals in the quartzite.

Devereux (1882), Irving *et al.* (1904) and Connolly (1927) consider that the gold is essentially detrital, derived mainly from the great Homestake lode and deposited in a nearby beach placer. Connolly lists a variety of evidence, which he thinks confirms the placer hypothesis. Among the various features are the facts that the gold in the conglomerates has all the physical characteristics of placer gold, and that it is invariably finer than the gold in the Homestake lode. The pyrite is said by Connolly (1927) to have been introduced during Tertiary time. This may be the case, although it seems more probable that the pyrite had an origin similar to that of the Rand, namely bacterial reduction of sulphates followed by fixation of available iron by the H_2S generated.

It has been said (Hosted and Wright, 1923) that the particulate gold and the gold in films and seams in the conglomerates and quartzites is of Tertiary age, related to Tertiary dykes and stocks that invade the Paleozoic rocks. There are certainly deposits of gold-tungsten, gold-silver and

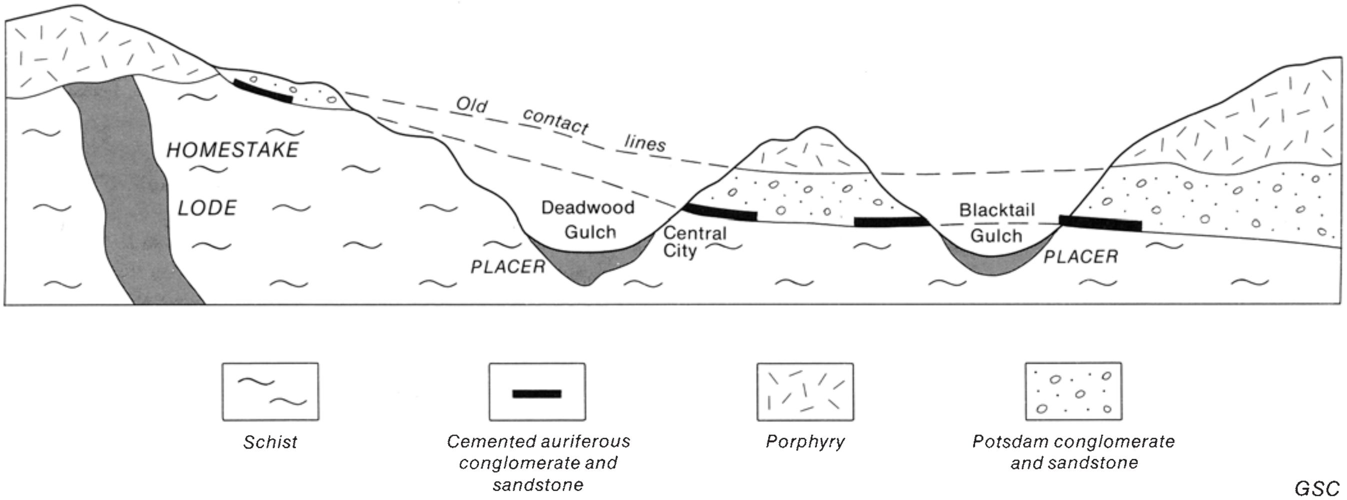

Figure 90. Generalized geological cross-section in the vicinity of the Homestake Mine, Lead, South Dakota (after Devereux, 1882). (No scale given on original.)

lead-silver that are of Tertiary age in higher parts of the Deadwood Formation, particularly in dolomites, in the general vicinity of the Homestake lode, but it is unlikely that the particulate gold and the gold in seams in the conglomerates and quartzites are of the same age. It appears more probable that the detrital gold has been partly remobilized by the intrusion of the Tertiary dykes. Devereux (1882) indicates that this has happened in some places, since he noted that the gold of the fossil placer had been partly dissolved out near a dyke. Contrast this with the same phenomenon noted in the Rand (page 324). One also wonders if the source of the gold in the undoubted Tertiary deposits is not to be found in the Paleozoic placers and in the Precambrian rocks rather than in Tertiary magmas. This theme will be developed more fully in the last section of this chapter.

Some of the sediments of Lower Eocene age in Texas contain gold (Dumble, 1913). Most of the auriferous beds are associated with the lignitic stage of the Eocene and include bedded clays and sands, the latter often containing pyrite and some iron oxides. Again we see a connection between gold and coal such as that which Tyrrell (1915) observed in the Edmonton Formation of Alberta as noted above. In fact the occurrence of auriferous sandstones and conglomerates with coal measures in various parts of the world is rather remarkable.

The thick clay beds (claystones) of the Shinarump Group (Triassic) in southern Utah are auriferous in places according to Lawson (1913). The gold, about 0.0025 oz/ton (0.085 ppm) is apparently very finely divided and is disseminated rather evenly throughout the colloidal clay materials (bentonite), which swell enormously when wet. Elsewhere in Utah, gold in ancient sediments seems to be widespread. Butler *et al.* (1920) mention the presence of gold in the sandstones in the San Juan River region and in the Triassic sandstones in the vicinity of the Henry Mountains.

Antweiler and Love (1967) investigated the gold content of Cretaceous and Tertiary sandstones and conglomerates in northwest Wyoming. Slightly modified, their conclusions are as follows:

1. Gold occurs in all areas of Cretaceous and Tertiary quartzite-bearing conglomerates that have been sampled in northwest Wyoming. The bulk rock analyses of the various formations are as follows (all values in parts per billion): Harebell Formation (latest Cretaceous), 65; Pinyon Conglomerate (Paleocene), 86; Fort Union Formation (Paleocene), 35; conglomerate of earliest (?) Eocene age, 94; Wind River Formation (early Eocene), 222; Pass Peak Formation of Eardley and others (middle(?) Eocene), 47; Miocene (?) conglomerate, 65; Quaternary deposits, 103.
2. The volume of low grade gold-bearing strata is so vast (50 mi^3 or more) that development of new mining and recovery methods designed for low-cost handling of huge quantities of relatively poorly consolidated material may eventually be justified.
3. Most of the gold was not derived from adjacent mountains but came from Precambrian and possibly Paleozoic quartzite in a now-buried uplift northwest of the Teton Range.
4. To analyze for gold in low concentrations, a method combining cyanide extraction and atomic absorption was found most reliable.
5. Analyses of 754 panned concentrates demonstrate some of the problems of recovering gold by mechanical and chemical methods and of evaluating various types of analytical data.

The detailed petrology and study of the paleocurrents of the Harebell Formation, Pinyon conglomerate and other coarse clastic deposits in northwestern Wyoming has been published by Lindsey (1972).

Turner (1903) describes a Cretaceous auriferous conglomerate from the Cottonwood Mining district, Siskiyou County, northern California. The conglomerate is part of a marine sandstone series and contains some fossil (shells) layers near the top. It has a maximum thickness of about 75 ft. Turner considered the gold to be of local origin derived from quartz veins in the metamorphic series all along the outcrop of the basal conglomerate. The conglomerate is said to have contained up to 0.175 oz/ton of conglomerate. The auriferous Cretaceous conglomerates have given rise to Pleistocene and younger placers in the Cottonwood valley. This is a case of an intermediate collector in the system – primary lode deposit → alluvial placer.

Attempts to mine a basal Cambrian conglomerate (Deadwood Formation) near Bald Mountain, Bighorn Mountains, Wyoming, were made in the early part of the century (Darton, 1906).

Barker (1969), searching for fossil placers, found only low contents of gold in the Precambrian clastic rocks of southwestern Colorado and northern New Mexico. In Colorado, the Vallecito Conglomerate and conglomerates of the Uncompahgre Formation of the Needle Mountains were sampled. In New Mexico, the Ortega Quartzite, the Big Rock Conglomerate Member, the Jawbone Conglomerate Member and the upper quartzite member of the Kiawa Mountain Formation in the Tusas Mountains and the lower quartzite member of the Ortega Quartzite and the conglomerate member of the Vadito Formation in the Picuris Range were sampled. All of these rocks contained less than 0.1 ppm gold; they apparently were derived from a terrane of quartzite, jasper, argillite and iron-formation that contained virtually no gold.

Auriferous sandstone, grit and conglomerate are widespread in the South Island of New Zealand, mainly in Otago and northeast Southland provinces. These include basal Cretaceous greywacke-quartz-schist conglomerates, basal early Tertiary sandstone, grit and quartz-pebble conglomerates and late Tertiary to early Pleistocene loosely cemented gravel conglomerates.

Several types of fanglomerates and cement conglomerates of Cretaceous age have been worked at a number of places in Otago, the most important being at Bluespur (Gabriels Gully), Wetherstons, Waitahuna Gully and Forsyth, where wedges of a cement conglomerate have been intermittently preserved by infaulting along a prominent fault (Tuapeka Fault). The workings of Gabriels Gully at Lawrence (the site of Gabriel Read's pioneer discovery of an economic gold deposit in South Island, N.Z.) are extensive and have produced some 200 000 oz of gold. Viewed at a distance the conglomerate has a bluish cast (hence the name Bluespur), but at close range it is seen to be greenish in colour due to a chloritic cement, which in places is also siliceous. The pebbles comprise schist, greywacke, quartzite and quartz of coarse gravel size with occasional cobbles up to 1 ft across. The sorting is relatively good, at least in the remnants of the conglomerate seen by the writer, and there is a fair stratification and some sandy and shaly laminae. Near the base the conglomerate contains some secondary pyrite. Most of the gold was evidently finely divided, and the pay streak was mainly localized near the bottom. The grade of the lower part of the conglomerate, as calculated from old records, was apparently about 1 ppm. Details of this conglomerate are given by Marshall (1918) and Williams (1974).

The basal early Tertiary sandstones, grits and quartz-pebble conglomerates rest mainly on the basement auriferous Otago (Haast Group) Schists of Triassic-Jurassic age and locally on Cretaceous fanglomerates. The age of the early Tertiary quartz-pebble conglomerates is said to be Oligocene, and most appear to be of fluvial origin. Some are up to 300 ft thick and commonly contain (secondary?) pyrite near their base. In places the gold appears to have been relatively evenly distributed through the conglomerate, but more generally the metal occurs over the schist basement in more or less oriented pay streaks. The gold is generally flaky and fine, the colours ranging from 0.5 mm down to paint and microscopic particles with occasional nuggets on the schist bottom. The fine division of the gold is considered by Williams (1974) to be the result not only of long attrition but also due to an origin from the weathering of auriferous pyrite from the lodes of the Otago Schist. Most of these conglomerates were worked where drawn up along schist blocks during late Tertiary orogenic movements. The grade of the early Tertiary conglomerates appears to have been about 0.07 ppm. Details of these conglomerates are given in Macpherson (1933) and Williams (1974).

Fanglomerates and various water-sorted beds of cream to reddish coarse gravels, loosely cemented and consisting mainly of schist and quartz pebbles were laid down along rising fault scarps and outward from these scarps during the late Miocene to early Pleistocene as a result of the Late Tertiary Kaikoura Orogeny, which affected much of the terrain underlain by the Otago Schists. These conglomerates were known to the early miners of the last century as the 'Maori Bottom' since they floor many of the auriferous Quaternary alluvials. In places these conglomerates are gently inclined to steeply dipping; most are auriferous to some degree. The richest sections have been worked at Nasby and in the Nevis Valley. Details and references concerning these auriferous conglomerates are given by Williams (1974).

Auriferous conglomerates, some worked extensively in the past, also occur in northwestern and southeastern Nelson. The former are considered to be of Oligocene age, rest mainly on Lower Paleozoic rocks containing gold-quartz lodes in places and consist mostly of quartz and slate pebbles and small boulders cemented in places by limonite and other ferruginous cement. In southeastern Nelson the basal Tertiary (Eocene) conglomerates are only slightly auriferous. Along the west coast certain Cretaceous and lower Tertiary conglomerates and sandstones are slightly auriferous in places. The Cretaceous Hawks Crag Breccia (a complex of poorly sorted coarse sandstone, siltstone, conglomerate and sedimentary breccia) is apparenly leanly auriferous in places. This breccia is also pyritiferous and in places uraniferous as in the Buller Gorge area, some of the uranium being in hydrocarbon. Williams (1974) has concluded that the uranium minerals are epigenetic and were probably introduced during the lower Cretaceous orogeny. Others (noted by Williams, 1974) have opted for a syngenetic-remobilization origin or for multiple mineralizations. The basal conglomerates of the Tertiary coal-measures in the Greymouth and Buller districts and other Eocene conglomerates in the area of the Grey and Inangahua rivers are slightly auriferous and in places pyritiferous. Details and a bibliography of all these conglomerates and breccias are given by Williams (1974).

Slightly auriferous conglomerates of early Pleistocene age have a widespread distribution in northern Westland occurring intermittently northwards from the Mikonui River at Ross to the Grey River. These auriferous conglomerates, which consist essentially of rusty greywacke, granite and schist pebbles, were known as the 'Old Man Gravels' and rest over large areas on a barren upper Miocene clay-glauconite formation known to the old placer miners as the 'Blue Bottom'. The source of the gold in the gravels is uncertain, some probably coming from the Precambrian(?) Greenland and Waiuta formations, which contain auriferous lodes, and some from the geosynclinal schists east of the Alpine Fault. The Old Man Gravels have been worked in places but apparently unprofitably. Their main importance is that they were probably one of the principal sources of gold for the younger Pleistocene and Recent gravels. Details of the Old Man Gravels are given by Suggate (1950) and Williams (1974).

Over the terrain underlain by the Otago Schists and their equivalents in Nelson and in the region in front of the glacial moraines that spread westward from the Southern Alps in Westland, New Zealand, several generations of auriferous conglomerates and gravels can be distinguished including those of Cretaceous, early Tertiary, late Tertiary to early Pleistocene and Quaternary age. The first three generations are described briefly above, and the last is mentioned in the previous section. The origin of the gold in these various generations of conglomerates and gravels is of interest. Williams (1974) thinks that most of the gold was ultimately derived from the weathering of the auriferous lodes of the Otago (Haast Group) Schists, the very finely divided variety in particular, coming from the breakdown of the auriferous pyrite that these lodes contain. Alexander McKay (1903), however, considered that the lodes in the Otago Schists were not abundant enough to provide the large amounts of gold won from the alluvials and conglomerates and thought that the bulk of the gold ultimately came mainly from the quartz laminae that are profusely developed in the schists. These are auriferous in places. Thus McKay concluded, "The gold of Otago must therefore be regarded as mainly having origin in the schists, and in near association with the quartz foliae that characterize the middle and lower divisions of the schists, and is but little due to the quartz reefs occurring in the same rocks."

These differences of opinion concerning the origin of the gold in placer fields arise from time to time among investigators, and there is as yet no certain solution or consensus. As mentioned later there is considerable evidence to suggest that at least some of the gold came from lodes, but that probably the bulk came from the weathering of the country rocks. With respect to the Otago deposits this multiple hypothesis would seem to resolve the problem. It might be added that in addition to the gold derived from the quartz laminae in the schists can probably also be added that weathered from pyrite, which is abundantly distributed through the graphitic phyllites and schists and other similar rocks of the Otago Schists.

The recycling of gold during sedimentation processes is markedly illustrated by the auriferous conglomerates and gravels of Otago. The initial auriferous rocks and lodes are those in or hosted by the Triassic and Jurassic Otago Schists. Their weathering initially gave Cretaceous conglomerates and sandstones locally enriched in placer gold. There followed then the recycling of gold from these conglomerates through Tertiary and Quaternary sediments with probable contributions at each stage from the auriferous Otago Schists and their contained lodes.

Numerous gold-bearing conglomerates, sandstones and quartzites ranging in age from Cambrian to Tertiary, occur in U.S.S.R. Ivensen *et al.* (1969) describe a number of them and give comparisons with similar deposits in other parts of the world. Most of the lithified types are low grade and have not been mined. The Lower Cambrian Khuzhir auriferous conglomerates and sandstones in East Sayan near Cheremkhovo rest on an Archean basement containing scattered gold-bearing quartz and quartz-sulphide stringers. The conglomerates are composed essentially of pebbles of quartz, quartzite, gneiss, granite, etc. heavily stained with iron oxides. They and their associated sandstones and siltstones represent alluvial river bed deposits. The gold is present as individual, fine grained, rounded particles and in quartz pebbles; some crystals and dendrites have also been noted. The general grade of the conglomerates appears to range from 0.2 to 0.4 ppm.

A great belt of auriferous conglomerates of Neogene age occurs along the southern flanks of the North Pamir and North Kunlun foredeeps of the continental molasse in U.S.S.R. and China respectively. They are the sources of most of the gold in the Quaternary placers of this region, which have been worked as far back as the 10th century. The source of the gold in the conglomerates is thought to be primary deposits in the Upper Paleozoic volcanic and sedimentary strata of the North Pamirs. Nearly all of the conglomerates are very low grade, ranging from 0.0075 to 0.750 ppm. Most of the gold is in the beds and lenses with large pebbles (boulder beds).

In summarizing this section on fossil gold placers we can state certain general paleogeologic and paleogeographic conditions that must exist in order to give rise to such deposits. These include, with brief notes of explanation:

1. An auriferous hinterland that has undergone gradual uplift, weathering, erosion and denudation. The primary source of the gold may have been (a) epigenetic gold-bearing deposits of many types; (b) disseminated gold in rocks especially those rich in pyrite and arsenopyrite, the gold being an intimate constituent of these sulphides; and (c) a combination of (a) and (b).

2. A favourable paleoenvironment for the concentration of gold in eluvial and alluvial deposits. The paleosedimentary conditions for the formation of fossil eluvial, alluvial, beach and aeolian placers have probably remained constant through time and hence are similar to those observed for modern placers as described above. By a study of the modern conditions one should be able to predict with some assurance the possible occurrence of fossil placers in any particular sedimentary column. Predictions may be difficult, however, where multiple erosion cycles have predominated in the geological history of a district.

Ivensen *et al.* (1969) have drawn the following conclusions with respect to the position and origin of ancient placers in the sedimentary and tectonic framework of an area.

1. Fossil auriferous placers are in most cases related neither to buried nor to relict paleoreliefs. Rather, they are related to various facies and belong to diverse formations. Most of the old placers are essentially part of the platform-type and orogenic, mainly continental, sedimentary formations. Economic gold deposits of the fossil placer type are known in various continents in geosynclinal formations of the Upper Archean and Lower Proterozoic periods, in the geosynclinal (?) and orogenic formations of the Lower and Middle Proterozoic periods that form part of the composition of the upper structural stage of the protoplatform, on the floor of the

platform mantle covering the Epikarelian platform, in continental autochthonous and allochthonous formations deposited at the late stage of the evolution of a stable platform region, in the orogenic sedimentary formations deposited at the late stage of development of mobilized portions of a platform and in the orogenic formation of foredeeps and intermontane troughs.

2. All of the deposits (i.e., the so-called fossil placers) are of sedimentary origin, and their gold has passed through various katagenetic (near surface) transformations, although the original pattern of the gold distribution has generally been retained. These gold-bearing deposits (placers) can be subdivided into two major groups: clastogene (placers in the proper sense of the word) and the group in which gold has been precipitated from finely dispersed suspensions mainly in a deltaic and marine littoral environment. The largest known Precambrian auriferous conglomerates, namely those of the Witwatersrand, belong to the second group. Ancient deltaic and marine littoral environments should, therefore, be scrutinized carefully for fossil gold deposits during prospecting.

Problems concerning the origin of placer gold

Despite the fact that the origin of gold in placers seems at a cursory glance to be relatively simple there still remain a number of mystifying features about gold in placers that have perplexed geologists for a century or more. Many outstanding investigations on gold in placers have been completed, but some of the problems remain unsolved. A few of the interesting problems with respect to the origin of gold in placers include the following: (1) the precise details of the origin of the gold in placers; (2) the reasons for the common occurrence of gold on the bedrock or on false bottoms; (3) the origin of nuggets; and (4) the reasons for the formation of a large number of productive gold placers in the Cenozoic era, particularly during Tertiary time in all of the climatic zones of the earth.

1. The precise details of the origin of the gold in placers has long been a problem in certain placer districts. In some districts one can point to gold-bearing deposits of various types as a source for the gold, but in others large auriferous deposits are lacking. In their place large quantities of widely distributed slightly auriferous quartz stringers, blows, boudins and irregular quartz masses are commonly found. These are said to have provided the gold to the placers. Examples of this feature are widespread, and many have been mentioned in preceding sections of the text. The localization of the principal placers of the Klondike within the confines of the Klondike Schist (Fig. 76) is a striking example. Another is found in the Bendeleben Quadrangle, Seward Peninsula, Alaska where practically all of the placers of the quadrangle occur in areas underlain by the York Slate, which is marked by intrusive bodies of acid to intermediate composition, small base metal veins carrying gold and major fault zones that have localized a plethora of auriferous quartz veinlets (Sainsbury, 1974). Finally, in still other districts it is evident from our analyses that the pyrite and arsenopyrite in graphitic schists and other pyritiferous rocks could have supplied large amounts of gold to placers during weathering of these rocks. A number of possible origins for the gold in placers are, therefore, evident—auriferous deposits, widely distributed slightly auriferous quartz bodies, various types of rocks, especially those bearing abundant pyrite and combinations of all three. Strange as it may seem, considering how long placers have been exploited, we have at present no certain idea of the contribution of each of the possible three sources of gold in the placers of any district. This is a problem that merits intensive research, for its solution could be particularly useful in geochemical prospecting as will be evident to anyone searching for economic primary gold deposits. If for instance the gold in placers or stream sediments is wholly or at least partly derived from primary quartz or sulphide deposits, use of the element as an indicator of such deposits is valid. If, however, the sources are widely distributed quartz blows, stringers, etc. or the country rocks, the use of gold as an indicator for the location of economic gold-bearing primary quartz or sulphide deposits is invalid. This problem is discussed further in Chapter V.

2. The reasons for the occurrence of pay streaks of gold on or near the bedrock or on false bottoms has intrigued many students of placers. Why should this be so, considering the great quantities of sand and gravel that often overlie the pay streaks? One would suspect on casual examination that the gold would be rather evenly distributed throughout the gravels and sands rather than concentrated in well-defined streaks.

Cheney and Patton (1967) mention that most economic geology text books do not mention this problem or treat it rather vaguely. These authors consider two general processes that might produce pay streaks on bedrocks or false bottoms—downward chemical movement of gold, which they dismiss; or downward physical movement of particles of gold through unconsolidated sediments, which they also consider improbable. They view the streaks on the bedrock as the results of extensive scouring (sluicing) of the whole sediment column in stream and river channels during floods of unusually large magnitude at irregular intervals of decades or even centuries.

Gunn (1968) commenting on these views concludes that there can be no all-embracing explanation for bedrock placers. From his experience, however, he believes that there is a downward physical movement of gold through the unconsolidated materials in placers. The source of the agitation (or jigging) to produce this movement is microseisms, one activating agency of these being moving water. Gunn (1968) also noted that in some placers the barren gravels may have been deposited under quite different conditions than those containing the pay streaks. Tuck (1968), after mentioning that bedrock concentrations are not the sole occurrence of gold in placer deposits, there being also concentrations on various types of false bottoms and as disseminations throughout some gravels, generalizes as follows:

> Commercial bedrock concentrations, in the case of stream deposits, are generally the result of a long period of erosion during which the stream is dominantly downcutting. Assuming a source of gold, weathering and erosion are separating and concentrating the gold from the country rock into the bottom of the valley. All during this period, which may represent several thousand feet or more of vertical erosion, gold as it is liberated is on or near bedrock since the stream is essentially flowing on bedrock. The action has been likened to that of a sluice box on a large scale, and there is no better analogy. Once gold reaches bedrock it generally remains

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> there. All during this period the stream valley is essentially youthful. Eventually a baselevel is reached, maturity is attained, and dominantly the stream begins to widen its valley.
>
> Characteristic of many of the important bedrock concentrations of gold is a narrow rich concentration meandering through a wider valley in which the bedrock of the bordering area may or may not have about the same elevation as that of the rich bedrock concentration. The bordering bedrock area may also have a concentration of gold, but it is of much lesser value than the narrow rich streak. In many cases, the narrow rich channel was high-grade enough to be hand-mined while later it and the bordering low-grade areas were dredged. The most logical explanation for this narrow rich channel is that it marks the bottom of the valley when the stream ceases dominantly to downcut and begins to cut laterally having reached a mature stage. The narrow rich channel is the concentration of gold from a volume of country rock very large relative to that which furnished the lower grade concentrations in the bordering area. It also logically follows that generally the narrow rich channel contains much coarser gold, and the particles have a higher gold-silver ratio, than the bordering area. Floods have their greatest importance in carrying gold to bedrock principally in the stage when the valley has reached maturity and is being widened with aggradation and degradation alternately occurring. At a still later stage aggradation becomes dominant, and the bedrock concentration formed during the youthful and early mature stages becomes covered with alluvium.

Tuck (1968) also reminds us that the history of placer streams and beach placers is much more complex than this simple exposition, pointing out among other factors, the necessity for a favourable erosion history and a suitable bedrock source of gold in the free state in particle sizes large enough to form commercial placers.

Krook (1968) claims that the climate is an important factor, a point also stressed by Mertie (1940). Krook says that the transition from vertical to lateral erosion and aggradation in a region is caused by a change in climate. As an illustration he mentions the case in some regions of the world where during Pleistocene time lateral erosion and aggradation took place during the glacial periods under periglacial conditions while during the warm interglacial intervals downcutting was extensive, giving rise to a series of river terraces. Under such conditions gold is highly concentrated in the lower terrace deposits and stream bottoms of a valley since with each phase of downcutting the gold is concentrated because it is transported only short distances horizontally, whereas the bulk of the sediment is swept far away downstream.

Kolesov (1975*b*), in a recent contribution to the problem of why placer gold tends to find the bedrock or false bottoms, maintains that the laws of hydrodynamic sorting in a flowing aqueous medium must be taken into consideration. He develops a number of equations which indicate that large gold particles will tend to accumulate in the bottom of the placer and that the finer particles will be distributed relatively uniformly throughout the cross section of the placer. Details should be sought in the original paper.

3. The origin of gold nuggets has long been a subject of discussion amongst students of gold placers. Two general theories prevail: one holds that the nuggets are formed mainly by chemical accretion processes; the other maintains that they are detrital in origin, had essentially the same weight as they now possess, but their shape and features are due to the rolling and hammering they have received as they have been moved along in the gravels. A third theory is a compromise holding that nuggets are partly detrital and partly chemical in origin.

There has been no consensus about the origin of nuggets for centuries. Albertus Magnus (1200–1280) mentions the problem in his *Book of Minerals* ((Wychoff, 1967, p.184) and concludes, "But gold which is formed in sands as a kind of grains, larger or smaller, is formed from a hot and very subtle vapour, concentrated and digested in the midst of the sandy material, and afterwards hardened into gold. For a sandy place is very hot and dry; but water getting in closes the pores so that the vapour can not escape; and thus it is concentrated upon itself and converted into gold. And therefore this kind of gold is better (finer)." From this we can assume that Albertus considered that alluvial gold is formed in situ. He was one of the first to advocate a chemical accretion process. His theory is repeated in the *Bergwerk-und Probierbüchlein* (1500) where reference is made to "gold generated in rivers and born in streams" (Sisco and Smith, 1949). In his *De la Pirotechnia* published in 1540, Vannoccio Biringuccio disagreed with the chemical theory and states that the gold of placers is merely transported by streams from oxidized and disintegrated bedrock deposits (Smith and Gnudi, 1959). Georgius Agricola, in his *De re metallica*, published in 1556, also adheres to this view (Hoover and Hoover, 1912).

Egleston (1881) considered that nuggets, and indeed most placer gold, were of chemical origin, the gold having been deposited from surface waters and waters that circulated through the placers. He explained the gold values on bedrocks in this manner, stating that as the gold-bearing solutions reach bedrock they can go downward no farther and precipitate their gold around nuclei due to the presence of reductants such as lignite, fossil wood, pyrite, etc. Gold in the upper few feet of bedrock in placer deposits was similarly explained.

Liversidge (1893*c*) reviewed the literature and theories on the origin of gold nuggets back to 1860. He mentions that A.R.C. Selwyn was the first to propound a chemical accretion theory for the origin of nuggets in the Victoria placers, Australia. Selwyn thought that the nuggets were chemically accreted about small nuclei of gold in the placers from large quantities of saline and acid thermal waters, which obtained their gold by percolation through the great thicknesses of gold-bearing gravels and sands. This took place during the period of great volcanic activity, which produced the basalts that cover the deep leads in some districts of Victoria. It should be mentioned in passing that a similar theory was advocated by some investigators for the deep leads in California.

Liversidge (1893*c*) carried out many experiments on the precipitation of gold on gold nuclei and conceded that gold nuggets could be formed in this way. However, he concluded that large nuggets have not been formed in situ in this manner. He stated that they had been set free from reefs and that any small additions of chemically precipitated gold were immaterial. In the case of gold dust and gold grains he thought the situation might be different for these expose a large surface and thus chemical accretion ("electroplating" he called it) may have had an appreciable effect in increasing the amount of this type of gold.

Maclaren (1908) reviewed all the evidence available about the origin of gold nuggets up to the turn of the century and concluded that chemical accretion played a large part in the formation of the nuggets and other gold particles in placers. Lindgren (1933) doubted that chemical accretion played any part in the formation of placer gold. Fisher (1935), who carried out an extensive investigation of the nature and structure of alluvial gold in the Morobe goldfield, New Guinea, concluded that the nuggets and flakes were derived mechanically from denuded gold-quartz veins or lodes. McConnell (1905) and Johnston and Uglow (1926) advocated the same origin for the placer gold of the Klondike and Cariboo respectively. Mustart (1965) also concluded that most of the placer gold he examined from the central Yukon was essentially detrital. Desborough (1970) and Desborough *et al.* (1970) have inferred that the placer gold they investigated from the western United States is detrital in origin. Boyle (1968*b*) has advocated a multiple hypothesis for the origin of placer gold, facets of which are amplified subsequently.

A number of criteria have been used by the proponents of the detrital and chemical hypotheses to support their contentions. These are listed with brief comments.

Criteria suggesting a detrital origin for nuggets and placer gold:

1. Gold placers are formed predominantly near the source of epigenetic gold deposits of various types. If chemical factors were involved one might expect that placers would be formed both near the source of the gold and at any distance where the chemical factors are favourable. Those who advocate a chemical mechanism might, however, retort that the presence of fine-grained gold near the source (epigenetic deposits) is the main reason for chemical accretion since the gold dust particles provide nuclei for precipitation.

2. Gold placers commonly contain nodules of quartz with masses of undoubted primary gold. Also large nuggets often have quartz attached to them in a manner similar to that found in primary quartz veins.

3. In many gold placers coarse gold is found near the source and increasingly finer grained gold downstream. This is suggestive of increasing abrasion and comminution of detrital material varying with distance travelled.

4. Gold in placers is commonly accompanied by a suite of heavy resistant minerals that accompany the gold in primary deposits, examples being scheelite, barite, pyrite and arsenopyrite. These minerals are obviously detrital and have no secondary chemical history. Gold probably behaved in a similar manner.

5. In a number of placers the gold contains essentially the same trace elements or trace minerals as those found in the gold of the primary deposits. This criterion is tenuous since most of the trace elements, having a siderophile (metallic) tendency, such as Hg, Ag, Cu, etc., may have precipitated with the gold on the nuclei of the nuggets. The traces of included minerals in nuggets are more difficult to explain chemically, but during accretion processes it is not uncommon for fine-grained particles of sulphides, tellurides, quartz, etc. to be incorporated mechanically in various types of pyrite nodules, iron concretions, etc. The same may take place in gold nuggets.

6. Gold in placers exhibits a crystalline nature similar to that of vein gold. There is commonly also a thin rind of relatively pure gold on some nuggets that has been interpreted as due to leaching of silver and other metals because these have a much higher solubility than gold. It should perhaps be noted in passing that not all gold nuggets, flakes and dust have a rind of purer gold, a feature noted by Stumpfl and Clark (1965) and many others. The crystallinity argument is not particularly valid. We assume that gold in epigenetic deposits, such as veins, is deposited from dilute solutions over a long period, and certainly this process gives rise to a good crystalline structure. There is no reason to assume that nuggets accreting gold from equally dilute surface solutions should not, likewise, have a good crystalline structure. The rind of relatively pure gold may be the surface expression of the precipitation mechanism. With time and growth of the nugget this rind is gradually incorporated into the crystalline fabric as a result of diffusion and recrystallization processes. Crook (1939) has suggested that recrystallization of gold nuggets is probably common. He noted that placer nuggets from 'new' or recent deposits show definite strain lines while nuggets from 'old' deposits where the gold has remained at rest for long periods of time have equiaxed (recrystallized) at normal temperatures due to cold working.

Criteria suggesting a chemical origin for nuggets and placer gold:

1. Gold and silver are constituents of most natural waters being relatively enriched in waters leaching primary gold and silver deposits. Gold and silver are also capable of migrating in permafrost (Boyle, 1951, 1965*a*) by a mechanism that is not entirely understood. Both elements seem to migrate in the permafrost while attached to water vapour molecules. Many years ago Freise (1931) pointed out that the *pinta que paga,* i.e., the 'paying spark' in gold placers in Brazil reappears after a number of years particularly when the exhausted goldfield has been hidden by the sun, by vegetation or other means. This he attributed to the transport of gold in humic (black) waters and its redeposition in the stream bottoms. As noted in Chapter II his theory of transport as gold humates has been verified by modern methods of analysis and experiment.

2. Nuggets usually have a mammillary appearance, which is suggestive of chemical accretion processes. Some have said, however, that this appearance is due to abrasion and rolling about in the placers. The microstructures of some mammillary nuggets in alluvial placers are zonal, and some are concentric, features that bespeak chemical accretion. Similar structures are often seen in gold in oxidized zones and in eluvial placers. In these situations the gold is undoubtedly accretionary in origin.

3. Gold crystals are often present in placers. They are relatively rare in most primary gold deposits. In placers the salient edges of the crystals are often sharp and well defined, indicating absence of agents of attrition or of solution. In other words many of these crystals grew in the placers.

4. Some nuggets and irregular particles of gold have crystal protuberances on their ends or on small projections. Such structures are rare in primary deposits. In the Urals, some rounded gold nuggets in the placers have developed crystal faces (Shcherbina, 1956*b*). Even more significant is the common occurrence of thin deposits and films of high purity gold on rounded particles of osmiridium (sysertskite) and

platinum in the gold placers of the Kuznetsk Alatau and Gornaya Shoria in U.S.S.R. (Syrovatskii *et al.,* 1969). These authors also refer to the work of a number of others who have noted chemical migration of gold in the Western Siberian placers. Voronin and Goldberg (1972) figure a number of occurrences of assymetrical secondary growths of gold on placer gold. They attribute this phenomenon to electrochemical processes in the placers, the small gold nuclei acting as collecting agencies.

5. Films, threads, wires, dendrites and paint gold commonly occur on stones in placers, on magnetite, attached to nuggets or limonite cement and especially in or near organic material such as buried wood, that has exerted a reducing action. 'New' or redeposited gold has been repeatedly observed in the Lena alluvial deposits, U.S.S.R., Nikolaeva (1958), however, considers that the amount of redeposited gold is very small and of no commercial importance.

6. Pyrite that has replaced fossil wood in some placers is invariably auriferous. Some say, however, that this is due to entrapment of flour or dust gold by the pyrite.

7. A number of investigators have shown experimentally that particles of gold accrete dissolved gold where reducing matter or minerals such as pyrite are available, as probably is always the case in placers. Goni *et al.* (1967) have demonstrated experimentally that gold nuggets can be formed from colloidal solutions of gold by compaction of the colloidally precipitated gold.

8. It has repeatedly been observed that there is an increase in the fineness of gold with increasing distance from the source. Pliny at the beginning of our era commented on this phenomenon. Thus, the fineness increases consistently in the order: primary deposit – eluvial placer – alluvial placer – marine placer all things being equal. Aberrations in the pattern are common, but in general the phenomenon appears to hold in many places according to Maclaren (1908), Lindgren (1933), Mertie (1940) and many others. With respect to the various elements present in placer gold there is a general decrease in the silver content and in some placers a gradual decrease in elements such as Fe, Mn, Cu, Ni, Pb, Bi, As, Sb and Te with distance from the source. Gorshkov *et al.* (1971) traced the fate of gold from the Khualazinsk primary deposit through eluvial and alluvial placers along the Tinkan River to a beach deposit along the Bay of Tinkan, far eastern southern maritime province, U.S.S.R. They noted a regular increase in the roundness of the gold particles, a general decrease in size and a fairly regular increase in fineness (800–860 in the primary deposit to 930 in the beach placer). They also observed a regular decrease in the content of Pb, Bi, Sb and Te in the gold in proportion to its distance from the source. Cu remained constant while mercury increased slightly. Internal structural changes were also noted with distance from the source, the most interesting being that the rind of purer gold on the particles increased in width, and there was an increase in the degree of recrystallization (60–75% recrystallized in the marine placers). The thicker rind in the marine placers was attributed to a greater degree of electrolytic corrosion by the seawater compared with the river water. The explanation of the increase in fineness of placer gold with increasing distance from the source has varied among those who have worked on the problem. Most investigators, including McConnell (1907), who first provided conclusive evidence for a rind of relatively pure gold on nuggets, have suggested that silver is progressively leached out of the gold because of the differential solubility of the two metals. Others have considered the explanation to be increasing precipitation of gold on small gold nuclei (dust) in the placers. Mertie (1940), who examined the problem carefully, considered the solution of silver from gold nuggets improbable. He pointed to the difficulty of removing silver from gold-silver alloys by the action of very dilute cold surface waters when concentrated inorganic acids were incapable of doing the job when the ratio of gold to silver is greater than 1:1.5 (400 fine) (the lower limit of gold for the removal of silver by the process of inquartation). Since most placer gold is at least 600 fine the amount of silver removed should be infinitesimal. Mertie and others have also pointed to the volume relationship of the so-called silver leached rinds compared to the total volume of gold. These rinds are very narrow (0.002 mm) and cannot have much overall effect in the fineness of the gold, especially where the gold is coarse (>1 mm). Furthermore, gold from which silver is leached is porous; microscopically a marked surficial porosity has been observed only rarely on particles of placer gold.

Mertie (1940) pictures the pay streak as a series of overlapping wedges of gold-bearing alluvium, which were progressively deposited upstream during a single erosional cycle. According to his view the downstream end of a pay streak is the oldest, and the upstream end the youngest, if the deposition has taken place during a single cycle of erosion. He also advanced the hypothesis that the apical part of a gold lode contains gold of higher fineness than its lower horizons. Taken together, he thought these two concepts lead directly to the conclusion that the gold of highest fineness is likely to be found in the downstream end of a pay streak, and that the fineness of the gold may diminish progressively upstream. This relationship was found to exist in some placer pay streaks in Alaska, but in others the fineness was observed to change erratically, or not at all.

On the other hand there is some experimental evidence that the fineness of placer gold can be increased by leaching and mechanical treatment. Koshman and Yugay (1972) were able to increase the fineness of gold by leaching with HF and H_2SO_4 and by grinding the gold. The first procedure removed both mineral and chemical impurities and the second mainly mineral impurities. Campbell *et al.* (1973) have reported similar findings with respect to acid leaching of placer gold. They noted that Ag, Cu, Hg, Pb, Bi and a number of other elements were removed and the fineness increased. How valid these experiments are with respect to the natural systems is a moot question. The leaches were far beyond any of the concentrations one might expect to find in natural waters.

9. Some gold nuggets in eluvial and alluvial placers appear to be greatly enriched in mercury compared with the gold particles in the primary deposits from which the nuggets presumably came. The reason for this may be that as the gold nuggets accrete in the oxidized zones of auriferous deposits they avidly collect the mercury liberated during the oxidation of minerals such as tetrahedrite and sphalerite. More data than are now available should be acquired on this aspect of the formation of nuggets since the enrichment of mercury may

assist in solving the perennial problem of the origin of gold nuggets.

The writer can add little to the vexed question of the origin of nuggets in placers. In the Yukon there is undoubted evidence that the gold in the oxidized zones is chemically accreted from very finely divided or lattice gold in pyrite and arsenopyrite. There, and elsewhere, there is positive evidence that the coarse gold in the upper parts of oxidized zones is finer than that in the primary deposits. What happens to the gold as it passes from the oxidized zones into the eluvium and from there into the alluvial placers and thence downstream is a problem that has not been adequately researched in the writer's opinion. There is certainly positive evidence that the soil solutions and stream waters contain both gold and silver, and all of the chemical evidence points to the probability that gold will be precipitated on any available gold nuclei provided reductants are present, which is nearly always the case in eluvium and alluvium. There is also considerable evidence that the gold of placer deposits has been extensively recrystallized, and the weight of the chemical evidence with respect to the relatively pure gold rinds on nuggets is that the rinds in most cases represent chemically precipitated gold and some silver rather than that the silver was leached from the surface layer. There may, however, be cases where the silver is leached from the surface of nuggets, but how this leaching could have proceeded throughout a nugget the size of a hen's egg, thus increasing its fineness considerably in excess of that found for the gold in the primary source, is difficult to understand.

These considerations have led the writer to conclude that the gold of placers is of both detrital and chemical origin. In some placers the detrital component may predominate; in others the chemical is more important. One should view the formation of gold nuggets in a dynamic sense, the agents forming them being both chemical and mechanical and their action being concomitant. As gold deposits weather down their particles of gold pass into the oxidized zones and then into the eluvium, in both of which they slowly accrete dissolved or colloidal gold (and some silver) from the oxidizing solutions in the veins and from the soil solutions. As the weathering cycle proceeds the material in eluvial deposits may be further decomposed, eroded, transported and redeposited. This can be effected by gravity, wind, streams, rivers, ice or by the surf of the sea, resulting in aeolian, alluvial and beach placers. During these movements the gold-silver particles may be hammered, comminuted and reduced to a flour, or, as is more often the case, especially in an aqueous environment, the small particles may be partly dissolved, the gold reprecipitated on the larger particles, and these may be cold worked and recrystallized as they are moved along in the placers. Since silver is more mobile (more soluble) than gold the chemical processes of solution and reprecipitation generally lead to an increase in the fineness of the gold flakes and nuggets with increasing distance from the source.

There is a tradition among placer miners that is centuries old, namely that gold 'grows' in placers. There is probably much truth in the adage.

Under certain conditions it seems possible that the gold in placers may be simply comminuted by mechanical abrasion, there being little or no chemical action. Yeend (1975) asked the question – What happens to a sand-size particle of gold as it travels along the bed of a river? – and sought to answer it by a laboratory experiment in which gold particles were tumbled in a mill with sand, sand and cobbles and only cobbles in a manner simulating a high-energy river environment. The results of his experiment are of interest: with sand and gravel, the common bedload of many placer rivers, gold was abraded at rates of 0.015 to 0.007 per cent (by weight)/h of travel (at 0.5 mi/h or 0.845 km/h). Cobbles, rather than sand, were responsible for most of the physical changes and abrasion of the gold. Ten gold fragments tumbled for 120 h with cobbles and water (no sand) were broken down to 68 recoverable fragments and lost about 25 per cent of their weight to particles smaller than could be recovered using conventional panning techniques. Gold, tumbled for 120 h with sand and water, lost less than 1 per cent of its weight. Gold was abraded faster by wet sand than by dry sand. Velocity appeared to be more important as a factor in the abrasion of gold than travel distance – a fourfold increase in velocity produced a tenfold increase in hourly abrasion rates of gold. Shilo *et al.* (*in* Petrovskaya, 1974) also carried out a number of simulative experiments on the abrasive action of ground quartz on placer gold. They noted that the gold grains were changed in form by erosive action and impact deformation. The average wear of the placer particles was 0.05 to 0.06 per cent/h.

4. The reasons for the formation and preservation of large numbers of productive gold placers throughout the world during Cenozoic time, particularly in the Tertiary period, as compared with earlier periods, has received little mention in the literature. But, before continuing the discussion of why these placers are so prevalent some of the general features of the distribution and nature of gold placers with time should be briefly reviewed. Large economic placerlike deposits occur in the Precambrian (e.g., Witwatersrand), but they are of restricted occurrence, of controversial origin, and if originally placers have been highly modified. The sedimentary rocks of the Paleozoic and Mesozoic contain a few fossil placers, but all are low grade, the gold being finely divided and generally widely disseminated throughout the conglomerates and sandstones. In Cenozoic sediments, particularly those of Tertiary age, gold placers are widespread occurring in practically every country. Many are or were phenomenally rich. An interesting feature about gold placers is the relationship of the size of the gold particles with time. Precambrian placers are all characterized by very fine-grained gold, often in the range 50 to 100μ. Paleozoic and Mesozoic gold placers are invariably also marked by fine-grained gold, but in places small nuggets a few millimetres in diameter can be found. They are, however, relatively rare. Tertiary and younger placers often contain coarse gold, nuggets weighing 1 oz or more being relatively common in places.

The Tertiary was a period of great volcanic activity and gold deposition in many parts of the world as noticed in the first part of this chapter (Fig. 7). But this abundant primary source of gold cannot be the sole parameter, or indeed a vital parameter, in the production of the many placers in the Tertiary and younger periods, for older eras were also marked by an abundant primary gold deposition, particularly the Precambrian.

The Tertiary was marked by extensive tectonic uplift in most parts of the world, and the paleoclimatologists tell us that the climate was generally hot and humid over almost the whole face of the earth, from the poles to the equator. Great forests of tropical to subtropical type also covered large areas of the land. The weathering, mainly lateritic, was deep and the downcutting by stream and river systems due to uplift was prolonged and extensive. Certainly these were optimum conditions for the formation of gold placers. But they are not unique in the geological history of the earth. Similar conditions probably existed in late Precambrian time, and certainly prevailed during parts of Paleozoic and Mesozoic time.

On close scrutiny it appears that neither source, tectonics nor climatic conditions are the decisive factors which gave rise to the multitude of placers in Tertiary and later times. One factor alone seems to be responsible, namely the generation of the sediments in which the placers occur. In nearly all Tertiary and younger gold placers the sediments are first generation or in some placers locally second generation. In other words the natural milling process has been relatively limited, and the gold has not been comminuted and dispersed. In older rocks most of the sediments represent many generations (cycles), and the natural milling has been extensive and pervasive. The result has been the wholesale comminution of gold and its dispersal throughout a vast volume of sandstones, conglomerates, etc. This is apparently why there is a diminution in the size of gold particles in placers with time. Recognition of these features is important in prospecting for fossil placers. First or second generation sediments in the sedimentary column are most likely to contain placers; only rarely in certain basins, such as the Witwatersrand, has the dispersed gold been reconcentrated into payable quantities by secondary (diagenetic) processes as outlined in a later section.

Miscellaneous sources of gold

Gold is won or can be won from a great variety of deposits not specifically mentioned in the above descriptions. These include the following:

1. *Nickel-copper ores associated with basic intrusions — Sudbury type:* The content of gold (and silver) in these ores is very low. In his studies Hawley (1962) found native gold (electrum) in only one of the deposits at Sudbury (the Frood deposit), and there it was relatively rare. The gold was rich in Ag, Pd and Ir and was predominantly associated with chalcopyrite. In the Noril'sk ores Razin and Yurkina (1971) found four gold minerals electrum, porpezite, argentocuproaurite and native gold. In the impregnation ores these minerals, all relatively high in Pd, are commonly intergrown with various platinoid minerals. Paragenetic relationships suggest that argentocuproaurite was the earliest to crystallize followed by porpezite, native gold and finally electrum.

In a study of the gold content of the Cu-Ni deposits in the Noril'sk region Vakhrushev *et al.* (1972) found great differences in the gold contents of the various sulphides. The highest contents (up to 9 ppm) were found in pyrrhotite, cubanite, chalcopyrite and pentlandite, and the lowest amounts in pyrite (<0.05 ppm) and sphalerite. They thought that this was good evidence for a difference in origin of the two suites of minerals, the gold-rich suite being essentially early (primary magmatic) and the gold-poor suite late postmagmatic (hydrothermal). They also made the interesting observation that pyrite related to trap (basic) intrusions commonly has less gold than that in skarn, polymetallic and vein deposits.

Keays and Crocket (1970) carried out an extensive investigation of the gold and platinoid content of the minerals of the Sudbury ores. Their averages in ppm for gold in the various minerals are: pyrrhotite (0.012), chalcopyrite (0.078), magnetite (0.0014), pentlandite (0.038) and gersdorffite (0.021). From these figures it is apparent that gold is associated mainly with chalcopyrite and pentlandite. In the deep ore zone of the Strathcona Mine at Sudbury, Chyi and Crocket (1976) found gold concentrated in pentlandite (up to 0.333 ppm). Pyrrhotite, chalcopyrite and magnetite contained up to 0.0277, 0.0351 and 0.011 ppm respectively. The general averages for pyrrhotite, chalcopyrite, pentlandite and magnetite were 0.0142, 0.0198, 0.1566 and 0.0056 ppm respectively.

A review of the literature on the distribution of gold in the Sudbury, Noril'sk and similar ores indicates that gold is commonly highest in content in the copper-rich (chalcopyrite, cubanite, etc.) ores and lowest in the pyrrhotite- and pyrite-rich ores, particularly the latter. The same relationship holds for the ores at Insizwa (Scholtz, 1936). In most nickel-copper ores of the Sudbury type, therefore, gold tends to follow copper and nickel and is commonly associated with the platinoids. Silver has a similar coherence particularly with copper. Most of the gold, at least about 75 per cent, occurs in the nickel-copper ores of the Sudbury type as native metal or as an alloy with platinoids, Ag and Cu. The remainder of the gold is probably present as an isomorphic mixture or in a finely divided state in the sulphides, particularly chalcopyrite, pentlandite, pyrite, arsenopyrite and pyrrhotite.

Our analyses and calculations of the content of gold and silver in the Sudbury ores as mined indicate average values of the order of: Au, 0.08 ppm; Ag, 2.3 ppm. Some of the so-called 'offset orebodies' are relatively rich in gold and silver; the chalcopyrite ores of the Vermilion deposit for instance average 1.9 and 100 ppm Au and Ag respectively. Other ores in these 'offset orebodies' that are rich in pyrrhotite have less gold and silver than the average quoted above.

The deposits of the Sudbury type yield considerable amounts of gold and silver throughout the world. The deposits at Sudbury produce some 2 million oz of silver and 50 000 oz of gold annually.

2. *Massive sulphide deposits containing essentially Fe, Cu, Pb and Zn sulphides in volcanic and sedimentary terranes — Noranda-Bathurst type:* In these deposits the contents of gold and silver are generally low. Most deposits rarely contain more than 0.05 oz/ton Au (1.7 ppm) and 5 oz/ton Ag (171 ppm). The highest gold contents found in deposits of this type appear to occur in the Kurokô ores of Japan (up to 1.5 oz Au/ton; 51.3 ppm). These are discussed separately below. Locally, small high grade massive sulphide deposits in many parts of the world may contain up to 2 oz Au/ton or more. The Au/Ag ratio in the Fe, Cu, Pb and Zn massive sulphide deposits appears to range widely from 0.006 to 1; the general average is about 0.025. Most of the gold in these deposits is generally present as the native metal or as tellurides; aurostibite has not been reported from massive sulphide deposits.

Some gold is also probably present in lattice sites in various sulphosalts, particularly tetrahedrite-tennantite and in chalcopyrite, bornite, pyrite and arsenopyrite. In many of these deposits the gold is associated with the copper-rich parts; in others with the siliceous pyritic or arsenopyritic zones. In certain deposits the gold appears to have been introduced during the galena-sphalerite stage. In this respect the gold mineralization behaves much like that discussed for gold-quartz veins. In the Phoenix Mine, Boundary district, British Columbia, Sinclair and Percy (1969) found, by multiple regression analysis of assay data for 220 samples, that there was a correlation of high gold and silver values with high chalcopyrite and pyrite content of the ore. In addition, a negative correlation between gold and lime-bearing minerals was observed. In the copper ores of the Cobar region, New South Wales the native gold is commonly associated with bismuth minerals and often with the sphalerite-galena stage of mineralization (Rayner, 1969). In the Bathurst, New Brunswick massive sulphide ores there is a positive correlation of gold with lead and zinc (galena-sphalerite stage) in some deposits; in others there is a correlation with copper; and in still others the gold appears to have been enriched at the pyrite-arsenopyrite stage. Some deposits with bornite are rich in gold, for example, the Urup deposit in the North Caucasus where up to 39.4 ppm Au in finely dispersed particles occurs in the bornite (Vikhter *et al.*, 1968). Others rich in arsenopyrite are, likewise, high in gold content. Such a deposit was the great Boliden deposit in Sweden (Grip and Wirstam, 1970). The ores were complex in this deposit and included arsenopyrite-rich bodies, gold-bearing quartz-tourmaline veins and large bodies composed mainly of pyrite and chalcopyrite. During the life of the deposit some 8 341 550 tons of sulphide ore were mined, containing 15.2 ppm Au, 49 ppm Ag, 1.42 per cent Cu, 25.1 per cent S and 6.91 per cent As. Much of the gold was microscopic and was present in the arsenopyrite; coarser gold occurred in the quartz-tourmaline veins.

In the massive sulphide bodies in volcanic and sedimentary terranes the silver is generally associated with the higher grade lead parts of some deposits and with the high-grade copper zones in others. Most of the primary silver is in either galena or tetrahedrite; some may be associated with sphalerite or chalcopyrite. In some deposits, much silver is contained in argentite, native silver, electrum, gold, sylvanite, altaite, stromeyerite and other silver-bearing sulphides, sulphosalts, tellurides and selenides. There is commonly no particular relationship between the silver and gold contents in the massive sulphide ores. As an extreme example one may mention the Kidd Creek deposit near Timmins, Ontario, which contains some 5 oz Ag/ton, whereas the gold content of the ores is nil or only traces. The native silver in this deposit, likewise, is devoid of gold in more than trace amounts. Supergene silver in the massive sulphide deposits occurs as the native metal, in chalcocite, covellite and acanthite, and in chlorargyrite, argentojarosite, etc. Supergene gold is invariably present as the native metal. Some of the oxidized zones of the massive sulphide bodies in volcanics and sediments are enriched in gold (*see also* Chapter IV).

In some deposits of this type there is commonly a complex relationship between gold, gold tellurides and the other constituents of the massive sulphide bodies. The classic example is the Horne Mine at Noranda described in great detail by Price (1934). He recognized three types of gold mineralization in this great orebody – gold in the massive sulphide deposits, gold in the flux deposits (silicified zones associated with the mineralization) and gold in the chloritic (alteration) deposits. Briefly the relationships of the gold in these three deposits are as follows according to Price:

(a) *Gold mineralization in the massive sulphide deposits:*

1) Gold and tellurides (especially the former) forming minute veinlets, irregular areas and dots in idiomorphic pyrite crystals.
2) Veinlets (predominantly gold) along the borders of pyrite crystals, between the pyrite and the adjacent sulphide.
3) Gold-telluride areas replacing pyrrhotite, the free gold particles being surrounded or 'sheathed' by tellurides.
4) Gold replacing chalcopyrite.
5) Gold and tellurides in veinlets and angular patterns replacing minute chlorite aggregates in the massive sulphides.
6) Quartz veinlets carrying gold and tellurides, cutting the earlier sulphides.
7) Type 5 repeated at the contacts of highly chloritized syenite porphyry where such material occurs in the midst of a large sulphide mass.

(b) *Gold mineralization in the flux deposits:*

1) Gold and tellurides in the forms given under Types 1 and 2 for the massive sulphides – in, and around, the borders of pyrite crystals.
2) Gold and tellurides in quartz veinlets cutting pyrite crystals.
3) Gold-telluride-quartz veinlets cutting the siliceous country rock.
4) Gold and tellurides replacing chloritized areas in and around isolated pyrite aggregates.

(c) *Gold mineralization in the high-grade chloritic deposits:*

1) The usual pyrite associations and textures given under (a) and (b).
2) Replacement of chalcopyrite by the tellurides and gold.
3) Replacement of the chlorite by tellurides in angular patterns.
4) Extremely minute gold and telluride veinlets in quartz aggregates in the massive chlorite.
5) Tellurides and gold replacing original magnetite.
6) Gold and telluride veinlets cutting chloritized metadiabase.

Throughout the world considerable amounts of gold and silver are won as a byproduct of the smelting and metallurgical treatment of the ores won from the massive sulphide bodies in volcanic and sedimentary terranes.

3. *Polymetallic vein and lode deposits containing essentially Fe, Cu, Pb and Zn sulphides in volcanic and sedimentary terranes:* These are widespread throughout the mineral belts of the world. Some are rich in gold (up to 1 oz/ton or more); others contain only traces. The silver content grades all the way from a few tenths of an ounce of silver per ton to 40 oz/ton or more. There is commonly no particular relationship between the gold and silver contents of the ores. Each deposit or group of deposits appears to be individualistic with respect

to the Au/Ag ratio, but statistically the majority of the deposits have a very low ratio.

Most of the gold in these deposits occurs in the native form, intimately mixed with the sulphides or as tellurides. Aurostibite has not been reported from these deposits. Some gold is also present as a lattice constituent of sulphosalts, particularly tetrahedrite-tennantite and of pyrite, arsenopyrite, bornite and chalcopyrite. Vikhter *et al.* (1968), who studied the precise form of gold in the pyritic polymetallic deposits in the northern Caucasus, U.S.S.R., found the metal to be present as flaky, spongy, streaky, dendritic and often filmy particles and aggregates. Gold tends to favour those deposits with a quartz gangue or with large amounts of arsenopyrite and pyrite, although this is by no means an invariable feature. Much of the silver in these deposits occurs in galena or in tetrahedrite-tennantite. Some of the deposits contain silver sulphides, sulphosalts and native silver. Many of the oxidized zones of these deposits are greatly enriched in gold, mainly in the native state, and in silver as the native metal or in chalcocite, covellite, acanthite, chlorargyrite, argentojarosite, etc. (*see also* Chapter IV).

Throughout the world large amounts of gold and silver are won as a byproduct of the smelting and metallurgical treatment of the ores from these deposits.

4. *Kurokô (black ore) deposits of Japan:* These deposits may belong partly in the massive sulphide category (2 above) and partly in the polymetallic category (3 above). They are, however, somewhat different from both and merit a brief description since they are commonly rich in both gold and silver, which are won mainly as a byproduct of the smelting of the Pb-Zn-Cu ores.

The Kurokô deposits are characteristically developed along the inner zone of Tertiary sediments and effusive rocks in northeast and southwest Japan. The geology near the numerous mines is complex and differs from district to district. Briefly, the host rocks are a volcanic sequence of tuffs, breccias, conglomerates, black shales, eruptive liparites, rhyolites, dacites and andesites and intrusive dolerites, andesites, diorites and quartz porphyries. The best general descriptions of the deposits are those by Kinoshita (1931), Horikoshi (1951–1952; 1969), Ishikawa *et al.* (1962), Urashima and Sato (1968), Matsukuma and Horikoshi (1970), Tatsumi and Watanabe (1971), Lambert and Sato (1974) and Ishihara *et al.* (1974).

Most of the deposits occur in the tuffs and shales and consist of veins, stockworks, irregular lenses, masses and nodules and conformable beds. They consist of an intimate mixture of very fine-grained sphalerite, galena and barite, usually accompanied by some chalcopyrite and often large masses of pyrite. In some areas large bodies of gypsum occur near the sulphide bodies. The name 'kurokô' derives from the black colour of the ores, but the colour as well as the texture and mineral composition varies considerably and a number of varieties are distinguished. These include massive 'kurokô', brecciated 'kurokô' banded 'kurokô', ôkô or yellow ore, which is a crystalline mass of pyrite and chalcopyrite accompanied by some quartz, and 'keikô' or siliceous ore, which is composed of silicified liparite or tuff heavily impregnated with pyrite, sphalerite, galena and other ore minerals. All of these varieties may occur individually or they may be intimately related in a single deposit.

The country rocks of the kurokô deposits are affected by marked alterations in places. These include propylitization, albitization, kaolinization and silicification. In some mines these alteration effects appear to be related spatially to the deposits; in others the relationships are not clear since the alteration effects spread throughout the country rocks.

The grade of the deposits is variable. Some deposits yield essentially lead, zinc and copper; others yield mainly copper or zinc. All types yield some silver and gold. The antimony-arsenic–rich ores containing fahlerz (tetrahedrite-tennantite) tend to have the highest contents of silver (up to 100 oz Ag/ton or more) and gold (up to 1.0 oz Au/ton or more). Most published analyses of these ores show that silver is always in excess of gold and that the Au/Ag ratio ranges from 0.005 to 0.05. Most of the gold in the kurokô-type deposits is evidently present as electrum, which according to Matsukuma and Horikoshi is generally concentrated in kurokô ore. The hypogene silver is largely present in tetrahedrite-tennantite and in a number of other silver minerals, including argentite, sternbergite, stromeyerite, jalpaite, polybasite, pyrargyrite, electrum and native silver.

A number of the deposits are deeply oxidized and present a vertical profile consisting of a surface gossan zone, a leached zone, an oxide enriched zone and a secondary sulphide enriched zone. The gossan is composed mainly of iron oxides and hydrated oxides and barite. The components of the sulphides are nearly completely leached out. The leached zone is depleted in copper and zinc and enriched in silver and gold. The oxide enriched zone may contain iron oxides, marcasite, pyromorphite, native copper, linarite, malachite, cerussite, anglesite and native silver. Copper and silver are greatly enriched in some of the deposits. The secondary sulphide enriched zone contains chalcocite, bornite, covellite, argentite, etc. It is enriched in copper, silver and a variety of other elements. The secondary sulphide zone is generally less than 5 m thick.

There has been considerable discussion on the origin of the kurokô ores. Some Japanese geologists consider them to be epigenetic replacement deposits derived by hydrothermal processes related to Tertiary magmatism. Certain investigators, noting the conformable banded nature of some of the ores, consider them to be of sedimentary (volcanic-exhalative) origin. Judging from the detailed descriptions of most of the deposits and from my own observations the weight of the evidence appears to favour an epigenetic origin.

The kurokô ores are interesting in that they are probably young equivalents of the massive sulphide deposits found in older rocks. Had they gone through a period of metamorphism and recrystallization they would probably present the features we now see in the older massive sulphide bodies found in Precambrian, Paleozoic and Mesozoic volcanic terranes. In this respect we may note that the Buchans lead-zinc-copper-silver-gold deposits in Newfoundland are remarkably similar to the kurokô bodies. The Buchans deposits, described in some detail by Relly (1960) and Swanson and Brown (1962) occur in the western part of the central volcanic belt of Newfoundland, which consists of a complex series of Ordovician andesites, dacites, rhyolites, volcanic breccias, tuffs and arkose. The orebodies consist of great lenses and irregular bodies of massive and disseminated sulphides in volcanic breccias and tuffs. The principal minerals are sphalerite, galena, chalcopyrite, tetrahedrite and pyrite. The main gangue minerals are barite and quartz. The wallrock alteration effects are those of sericitization, silicification, pyritization and chloritization. The grade of the ore is about 15.5 per cent Zn, 7.8 per cent Pb, 1.4 per cent Cu, 3.5 oz Ag/ton and 0.05 oz Au/ton. The silver occurs in the native form, in argentite, in galena and probably also in the chalcopyrite and tetrahedrite. There are no obvious correlations of the two precious metals with Cu, Pb or any other element in the orebodies.

5. *Disseminated deposits – porphyry Cu-Mo type:* These deposits generally contain only low contents of gold and silver. Overall the deposits average about 0.01 oz Au/ton and 0.1 oz Ag/ton, although certain heavily mineralized sections of some deposit may contain 2 to 5 times this content of the precious metals. Many of the deposits are deeply oxidized, and both the oxidized zones and secondary sulphide zones are commonly enriched in both gold and silver (*see also* Chapter IV).

The nature of gold in porphyry Cu-Mo deposits has received little study. Probably much of the gold is present in the native state and as tellurides in the hypogene ores. In the supergene sulphides the same states may predominate, although there may be considerable amounts of gold in lattice sites in minerals such as chalcocite and covellite. In the oxidized zones most of the gold is present in the native state. In a Transcaucasian Cu-Mo deposit apparently of a porphyritic nature, Karapetyan (1962) found the gold to be present in the primary ores in the following forms: (1) coarse-grained native gold in the interstices of the sulphides and other associated minerals; (2) finely dispersed and submicroscopic gold in the early sulphides (pyrite, chalcopyrite, bornite, etc.); and (3) gold tellurides. In the oxidized zones most of the gold is present in the native form. Most of the gold in a complex copper porphyry deposit in the Almalyk region U.S.S.R. was deposited during two major stages of mineralization according to Meshchaninov and Azin (1972). These are indicated in the five stages represented in the deposit as follows: (1) pre-ore; (2) Cu-Mo (gold-bearing); (3) Pb-Zn; (4) Au ore in stockworks and veins; and (5) rare metal.

The Island Copper Mine, Port Hardy, Vancouver Island, British Columbia is characterized mainly by the introduction of pyrite, chalcopyrite and molybdenite into extensive fractured and brecciated zones. Much of the gold in the porphyry-type deposit occurs as ovoid and hackly particles of free metal with an average size of 15μ. The greater part of this gold is associated with the pyrite and chalcopyrite. Our studies indicate that there is no particular correlation between the gold content and that of Cu, As, Sb, Bi, Se and Te in the deposit. The grade of the ore in the Island Copper Mine, as calculated from production records, is 0.004 oz Au/ton and 0.02 oz Ag/ton. Similar grades occur in certain of the other porphyry copper deposits in British Columbia, e.g., Granisle deposit – Au–0.004 oz/ton; Ag–0.04 oz/ton, whereas in other deposits the grades are very low in gold, e.g., Brenda deposit – Au–0.0004 oz/ton; Ag–0.03 oz/ton.

Gold and silver, like molybdenum, correlate closely with the cupriferous zone above the Kalamazoo porphyry copper deposit, San Manuel district, Pinal County, Arizona (Chaffee, 1976). The highest concentrations of both gold and silver are mostly in the potassic alteration zone, and gold is also concentrated to a certain degree in the propylitic zone. Chaffee concluded that Cu, Mo, Au and Ag shared a common genesis, with gold having a broader dispersion with respect to the 0.1 per cent copper boundary and the pyrite aureole.

In the great Bougainville porphyry copper orebody in New Guinea, chalcopyrite and pyrite are the principal ore minerals, with a little bornite. The tenor of the gold varies directly with that of copper. Reserves are estimated to be 900 million tons containing 0.48 per cent Cu and 0.018 oz Au/ton (Knight *et al.*, 1973).

The production of gold and silver from porphyry Cu-Mo deposits is considerable. In fact a large proportion of the gold and silver production of the United States comes from these deposits. For instance some 200 million oz of silver and 11 million oz of gold have been won from about 1 billion tons of ore in the Bingham Canyon deposit in Utah (Peters, *et al.*, *in* Titley and Hicks, 1966). Some deposits evidently produce much more gold than others since Kesler (1973) has shown that porphyry copper deposits are divisible into geologically real copper-molybdenum deposits with relatively little gold and copper-gold deposits enriched in the precious metal.

Much of the gold in porphyry-type copper and molybdenum deposits is associated with or contains small amounts of palladium.

6. *Pyritiferous shales and schists and cupriferous shales and schists – Kupferschiefer type:* Most pyritic shales contain only traces of gold, the highest contents recorded being about 1 ppm Au. Oil shales, are, likewise, generally low in gold content. Commercial recovery from these types of rocks is not feasible at present, but may become so in the future when such rocks are mined for their bitumen, uranium and base metal content. Commercial recovery of gold and silver from oil shales and tarry residues is suggested in a patent by Petty (1968).

The copper shales and schists are commonly enriched in silver (Boyle, 1968*b*) but generally contain only traces of gold. Our analyses of samples from the White Pine, Michigan deposits show them to contain only <0.005 to 0.020 ppm Au, the average being <0.005 ppm. The silver contents range from<0.4 to 33.3 ppm, the average being about 4.5 ppm. The ores of the Kupferschiefer average about 0.5 ppm Au and 180 ppm Ag. The Zechstein cupriferous black shales of the Fore Sudeten Monocline in Poland are, likewise, low in gold, containing usually from 0.01 to 0.3 ppm (Salamon, 1976). The silver content by comparison averages about 150 ppm with local concentrations up to 5700 ppm or more. Some of the gold is present in electrum, the remainder in native silver and a great variety of silver and copper sulphides and sulphosalts.

Some pyritic carbonaceous slates and schists are slightly auriferous where they contain extensive seams, blows and boudins of quartz. The gold is epigenetic in situ, although it may have been concentrated in the quartz or adjacent schist from the sedimentary beds during metamorphism. Such types of deposits are widespread in many terranes of sedimentary rocks, but few contain more than 1 ppm Au when bulk sampled. One deposit at Blue Hill, Tallapoosa County, Alabama has been studied by the U.S. Bureau of Mines (Sullivan *et al.*, 1969). The average of analyses of the graphitic schist was

0.08 oz Au/ton (2.7 ppm). Most of the gold was found to be free and a concentrate assaying 24.3 oz Au/ton was obtained. Jigging, tabling and amalgamation recovered 86.5 per cent of the gold from the schist.

7. *Cupriferous and argentiferous sandstones — Red-bed type:* Some of these deposits are markedly enriched in silver (Boyle, 1968*b*), but most contain only traces of gold. The writer's analyses of these deposits from various parts of the world show that the ores generally contain less than 0.002 oz Au/ton (0.06 ppm). Kobe (1960) reports that the red-bed ores at Negra Huanusha in central Peru average 3.21 per cent Cu; 2.92 oz/ton Ag; and 0.006 oz/ton Au. The writer's limited research on the red-bed deposits of New Brunswick and Nova Scotia indicates that chalcocite is the principal carrier of gold and silver. Contents up to 0.08 ppm Au and 445 ppm Ag have been recorded from pure chalcocite from the Dorchester Mine and elsewhere in New Brunswick. Tarr (1910) reports up to 31.35 oz Ag/ton (1083 ppm) and 0.1 oz Au/ton (3.4 ppm) in the chalcocite from the red-bed deposits of Oklahoma. Shpora *et al.* (1972) comment on the relatively low content of gold in the copper-bearing sandstones of Naukat, U.S.S.R. They remark that the gold content in the sandstones is not anomalously high in comparison with the gold content of other sedimentary rocks.

8. *Carbonatites:* These complexes contain small amounts of silver (up to 4.5 ppm), but their gold content is commonly very low (<0.01 ppm). Some complexes such as those that produce copper (Phalaborwa, South Africa) contain native gold and/or electrum and/or native silver (Forster, 1958).

9. *Platinum deposits:* Reefs and sulphide segregations associated with basic and ultrabasic rocks such as the Merensky Reef in South Africa are slightly auriferous, and some gold is won from treatment of the platinoid concentrates, which as a whole average about 0.25 oz/ton of rock. In some samples from the Merensky Reef Crocket *et al.* (1976) found that Au and Pt did not show a clear enrichment in separated sulphides and oxides, but the two metals exhibited a maximum content (Au–3.4 ppm; Pt–15.0 ppm) immediately above the marker chromite seam and coincident with maxima for sulphur, nickel and cobalt. There is a considerable reserve of gold in the platiniferous nickel-copper sulphide segregations of the Great Dyke of southern Rhodesia. Panned concentrates from some of these segregations run 0.6 per cent gold (Worst, 1960) (*see also* 1 above).

10. *Black sands:* Certain black sands in many parts of the world contain small amounts of gold which can be won as a byproduct of their mining for magnetite, ilmenite, rutile, zircon, etc. Such sands occur on Graham Island, Queen Charlotte Islands, British Columbia (Mandy, 1934), along the west coast of South Island, New Zealand (Williams, 1974) and elsewhere.

11. *Sediments of the sea:* All sediments of the sea are very slightly auriferous, averaging about 0.005 ppm Au. Some such as those in parts of the Red Sea are slightly auriferous and argentiferous containing an average of 0.66 ppm Au and 28.4 ppm Ag as compiled from the available data (*see* Table 14). These sediments are also enriched in Cu and Zn. Several methods of winning the base and precious metals have been suggested (Degens and Ross, 1969; Lassiter, 1971). The subsea gold resources of the world are discussed by McKelvey and Wang (1970).

12. *The sea:* Seawater contains an average of 0.02 ppb Au and 0.2 ppb Ag (*see also* the section on natural waters in Chapter II). Both elements are also present in marine manganese nodules and other marine sediments as noted above. The trick is how to win these precious metals economically. The economics of winning metals from the sea are discussed in detail by Mero (1965).

> The observations among the gold-bearing rocks of the Southern States seem to show that the precious metal was originally deposited in the beds of various sedimentary rocks, such as slates, quartzites and limestones, and that by subsequent process, it has been, in some instances, accumulated in the veins which intersect these rocks.
>
> –Sir William E. Logan, 1860

Origin of gold deposits

In the foregoing descriptions of the various types of gold deposits, probable origins for the principal types have been suggested. It now remains to summarize these and to amplify some of the concepts. The origin of typical epigenetic deposits such as gold-quartz veins is discussed first, and this is followed by an outline of the probable origin of the enigmatic auriferous quartz-pebble conglomerates, typified by the world's largest gold deposits, namely those of the Witwatersrand.

Epigenetic gold deposits

Epigenetic gold deposits include those developed in skarns; in gold-quartz lenses and silicified zones in fractures, faults and shear zones; and in various replacement and disseminated bodies in iron-formations, limestones and other chemically receptive rocks. The essential features of all of these deposits is that they were dependent upon the presence of preexisting structures or chemically receptive rocks within which some medium or other has deposited the gold and its accompanying gangue.

The source of gold and its associated metallic and gangue elements in epigenetic deposits has long been the subject of debate among geologists. Four distinct possibilities have been considered since the time of Agricola. These can be conveniently tabulated as follows:

(1) The gold and its accompanying elements came from a deep source in the earth. The mantle is often mentioned as a possibility, but even deeper regions have been suggested. An origin based on these sources is commonly referred to as an abyssal origin.

(2) The gold and its accompanying elements came from a crystallizing magmatic body. Basic magmas are favoured by some investigators (e.g., Bilibin and others); more acid magmas such as those that give rise to granodiorites and granites appeal to others (e.g., Emmons, Lindgren and others). This source is the basis of the magmatic hydrothermal theory.

(3) The gold and its accompanying elements came from the country rocks that enclose the deposits or from rocks that lie above, below or lateral to the deposits. This is the basis of the various secretion (lateral, metamorphic, etc.) theories.

(4) The gold and its associated elements came from a weathered surface and were carried into favourable structures by descending meteoric waters. This mode of origin can, in general, be dismissed for practically all types of epigenetic gold deposits. Such a process seems quite incapable of producing the varied types of epigenetic gold deposits that occur in mineralized volcanic and sedimentary terranes. Furthermore, the regional zonation of certain minerals and elements in epigenetic gold deposits, the marked differences in elemental precipitation as the mineralization progressed in many areas, the characteristic wall-rock alteration effects and the remarkably low solubility of elements such as gold and lead in normal groundwaters all militate against the weathering hypothesis. For these reasons we shall not consider it further.

Abyssal theories of origin

These theories generally postulate that the constituents of ores in veins and other epigenetic deposits came directly from deep zones within the earth in the form of diffusing elements, as vapours, in a molten state or in various types of aqueous solutions. It is important to distinguish the details of this mechanism clearly, since ultimately all crustal rocks and the constituents of ores can be traced to deep sources within the earth. Since René Descartes first suggested the idea in 1644, abyssal sources have long been advocated for gold and other metallic ores, the mantle appealing to many as the most probable zone from which the metals, sulphides and gangue were extracted. The precise nature of the mother rock or magma is usually referred to in the vaguest of terms, although some seem to think that it is basic or ultrabasic in composition. Brown (1948), however, considers that a metal sulphide layer exists in the upper part of the mantle, ready to be tapped when channelways such as faults and fractures are opened by tectonism in the crust above. Quiring (1954) postulates a chalcosphere in the earth from which the sulphides and metals are derived. Kennedy (1948) considered that ore deposits with plutonic associations were derived from magmas that resulted from remelting of the deep parts of the granitic layer of the earth. The granitic layer he envisaged as consisting of granitic igneous rocks and metamorphic rocks, mainly of sedimentary origin, that were enriched in particular elements in certain zones. Remelting of parts of these zones, attended by concentration of the elements in orebodies, he thought could explain the phenomenon of metallogenic provinces.

All of the abyssal theories put the responsible source rocks or mother substance well out of reach of any modern techniques of examination and analysis; hence, they remain highly speculative, unsupported by any facts. There are, however, some manifestations that may suggest a deep source for gold and its accompanying elements. For instance, many epigenetic gold deposits are closely associated with volcanic rocks, examples being particularly common in Precambrian and Tertiary terranes. Since it is generally assumed that the volcanic rocks were derived from magmas originating deep within the earth, probably the mantle, the gold and its accompanying elements may have had a similar origin. The evidence of the association of gold deposits with volcanism can, however, be interpreted in other ways as will be discussed later. Here, it is sufficient to note that there is generally a considerable time interval between the stages of volcanism and mineralization. This interval is marked in most places by metamorphic, granitization and/or igneous injection events, usually of a complex nature. The other feature that could be taken to indicate a deep source for gold and its accompanying elements is the common occurrence of gold deposits in or near great fault and fracture systems that run for many tens of miles, examples being the Kirkland Lake–Larder Lake–Cadillac 'break' of Ontario and Quebec; the Giant-Campbell System at Yellowknife, Northwest Territories; the Mother Lode System of California; and the Champion System of the Kolar goldfield in India. The great linear extent of these systems suggests that they cut deeply into the earth, perhaps to the mantle, from which they may have derived the constituents of their gold lodes. This possibility was examined in the Yellowknife district by the writer (Boyle, 1961*a*) where the Giant-Campbell shear zone system (Archean age) some 15 mi in extent is cut by a great series of steeply dipping late faults (Proterozoic age) many of which can be traced for more than 50 mi (Fig. 17). If the mantle or some other deep zone were the source of gold and its accompanying elements, one would expect both systems of faults to have been mineralized with gold since both evidently cut deeply into the earth. Such is not the case: the Giant-Campbell System is highly auriferous, the late faults, even where they are extensively mineralized with quartz and some pyrite, are essentially barren. The reasons for this difference in mineralization are complex but can be related directly to metamorphic events. The auriferous Giant-Campbell and its subsidiary systems were formed during the late stage of regional metamorphism, granitization and granitic intrusion of the greenstone belt. As the systems dilated, the constituents of the gold-quartz lodes, mobilized from the greenstone pile, were drawn into and precipitated in favourable structural sites in the systems. When the late faults were formed the processes of regional metamorphism, granitization and granitic intrusion were not operative, and hence gold was not mobilized and concentrated from the host rocks.

Magmatic differentiation theories

The basis of these theories is that the gold and its accompanying elements came from a crystallizing magmatic body injected into or derived from crustal rocks. Two general concepts have been developed. One envisages differentiation of the magmatic body to give an ore magma composed of fused silica, carbonates, sulfides, metals, etc. from which the vein constituents crystallized. The other postulates that as the magmatic bodies crystallize they yield hydrothermal extracts containing the metals, sulphides and gangue elements such as silica, all of which are deposited as constituents in the epigenetic gold deposits. The precise origin of the magmatic bodies, which are said to give rise to the ore constituents, is rather vague in the literature, especially when specific mineral belts are discussed. Following R.A. Daly (1914) most of the older investigators apparently thought that the magmatic bodies were of subcrustal origin, derived from the differentiation of primary basaltic magma representing a fused part of the mantle or some other deeper zone in the earth. In recent years granitization and/or anatectic processes involving crustal rocks have been more popular as the source of magmas. The rocks most commonly thought to give rise to granitic magmas by these processes are pelitic sediments, although piles of such sediments and volcanics have also been suggested as the original materials. The phenomenon of granitization is discussed at length by Read (1957) and Reynolds (1946, 1947) and its relationship to ore genesis by Guimaraes (1947), Sullivan (1948) and MacGregor (1951). The last investigator summed up his views as follows: "The conclusion is reached that the origin of gold is the Sima where it is diffused in the glassy or crystalline basaltic rock. From time to time the Sima in a molten state ascends fissures through the Sial and flows out in vast fields of lava. In belts of mountain-building the granite of the Sial fuses and the more fluid parts of it ascend to fill domelike chambers formed by the subsidence of the overlying rocks. Sinking fragments of basalt dissolve or disintegrate in the molten granite. Metallic sulphides and carbon dioxide from the sunken rocks react with silica, water and other fluxes in the granite to form solvents of gold. As the granite consolidates, the solutions are ejected upwards to form mineral deposits in the upper, already crystallized portion of the granite and in the overlying rock."

In recent papers Smirnov (1968, 1976) outlined current views in U.S.S.R. on the sources of ore-forming material. Three principal groups of ore-forming source material are assumed: (1) juvenile sources associated with deep-seated subcrustal magmas of basaltic composition; these give rise to a basaltophilic group of metals including Fe, Mn, V, Ti, Cr, platinoids, Cu and Zn; (2) assimilative sources in shallow palingenetic (anatectic) magmas within the predominantly granitoid portion of the crust of the earth; from these derive a granitophilic group of elements including Sn, W, Be, Li, Nb and Ta; and (3) filtration sources in which ore-forming material is leached along the circulation pathways of aggressive hydrothermal solutions that differ widely in origin (magmatic, metamorphic or exogenetic). Gold deposits can evidently derive from all three source materials. Thus one finds in the voluminous Soviet literature on mineral deposits a number of papers that deal specifically with gold deposits in accord with these conceptual ideas. Investigators supporting the magmatic derivation of gold include among others Rozhkov (1968*a*, 1970), who advocates a paragenetic relationship of gold deposits with magmas of both subcrustal (simatic origin) and intracrustal (granitic and andesitic) derivaton; Il'enok (1970), who relates epigenetic gold deposits of various types to a variety of magmas; Shcherbakov (1970), who maintains that both basaltic and granitic magmas are important sources of gold; Volarovich and Shilin (1971), who connect gold deposits with the crystallization of gabbro-granodioritic magmas and maintain that the gold content of rocks from these calc-alkaline magmas increases with the differentiation sequence gabbro to aplite; Karelin *et al.* (1974), who concluded that the source of gold is deep magma chambers; and Marakushev (1977), who on thermodynamic grounds relates endogenic gold deposits to diorites, granodiorites, plagiogranites and granites. Among those supporting granitization, remobilization, redistribution and regeneration theories are a number of investigators who describe the gold deposits of the Soviet far east in the book edited by Radkevich (1966). Some of these have the idea that the gold deposits are regenerated by assimilation of ancient metamorphic horizons by anatectic magmas. In other publications, Moiseenko *et al.* (1970) consider that much of the gold in deposits is redistributed as a result of the destruction of minerals containing trace amounts of gold during postmagmatic alteration processes; Shcherbakov (1970), Shcherbakov *et al.* (1972) and Shcherbakov *et al.* (1973) maintain that endogenous gold deposits may be derived not only from magmas but also from anatectic granitoids and from piles of rocks with higher contents of gold while they are undergoing hydrothermal and contact metamorphism; and Perelygina (1973) advocates a Mesozoic rejuvenation of the gold in the Aldan Shield for the origin of the deposits in the cover rocks of this massif.

The ore magma is an old concept, originally postulated by James Hutton in 1795. Since then it has been considerably amplified and used to explain auriferous quartz deposits in many parts of the world. Thomas Belt (1861), enquiring into the origin of the auriferous quartz veins in Australia, concluded "that in these veins the distribution of gold, and the structure and arrangement of the quartz, are explained by the theory that they are fissures that have been filled with molten silica containing entangled metallic vapours." Belt later worked in Nova Scotia and entertained a similar origin for the veins and saddle reefs in the Meguma Group. J.E. Spurr (1923) postulated a molten origin for gold-quartz bodies in his classic treatise on the ore magmas. Farmin (1938, 1941) has explained the gold-quartz veins of Grass Valley, California by injection of a siliceous fluid rich in CO_2, and Bichan (1944, 1947) advocated deposition of gold from silicothermal melts for most epigenetic gold deposits.

Originally, the derivation of gold-quartz veins from siliceous melts seems to have gained favour as a result of the mistaken idea that silica (quartz) is insoluble in water and from the general observation that many gold-quartz veins are closely associated with igneous bodies especially dykes, some features of which resemble those found in veins, viz. chilled dyke contacts, which are somewhat analogous to fine-grained quartz borders in veins. Later the presence of unsupported inclusions of wall rock in gold-quartz veins was taken as evidence that the depositing medium was dense enough to float the fragments or sufficiently viscous to support them. Finally, the sharpness of the contact between the vein material and wall rock and the absence of replacement of the wall rock was assumed to indicate that the depositing medium was too viscous to penetrate discontinuities such as grain boundaries in the wall rock.

The ore magma theory of the origin of gold-quartz veins has not been favourably received from its inception. Kirwan (1799), criticizing Hutton's ideas, showed that silica is soluble in hot water. The observation that quartz veins show a close association with igneous bodies in some mineralized areas has stood the test of time, but most investigators doubt that quartz veins are magmatic offshoots of such bodies. The unsupported wall-rock inclusions and sharp vein contacts as evidence of a melt injection have also been questioned, even at Grass Valley where such phenomena are widespread (Johnston, 1940). It is considered more probable that the first is due to repeated movement and deposition of quartz along the veins, during which process residuals of unsupported wall rock are left within the resultant quartz bodies. The sharp contact relationships have, likewise, been reinterpreted as due to similar physico-chemical relationships existing between the wall rocks and the quartz-depositing medium.

A magmatic source for the metallic and gangue elements in hydrothermal deposits has been favoured by many geologists since Elie de Beaumont and others first suggested the possibility more than 125 years ago. The modern theory envisages a crystallizing magma during its last differentiating stages giving off water and other volatiles that transport the metals and gangue elements to their depositional sites in fractures, faults, shear zones and other favourable locales. The variations on this theme are many, and the physico-chemical mechanisms conjured up to explain the various manifestations of the process would fill many volumes. Some recent concepts are outlined in the book edited by Barnes (1967). In the present century most epigenetic gold deposits have been explained by the magmatic hydrothermal theory particularly by such astute observers as Pošepný (1902), Lindgren (1933), Emmons (1940), Bruce (1937*a,b*), Moore (1940), Bateman (1950) and a number of U.S.S.R. geologists including Bilibin, Betekhtin, S.S. Smirnov and others (Shilo, 1971; Ivankin and Rabinovich, 1972). As noted in a previous part of this chapter, the auriferous quartz-pebble conglomerates of the Witwatersrand have been similarly explained by Graton (1930). Emmons (1924, 1937) in his assessment of the space relations of gold deposits to granite batholiths laid great stress on the area of exposure of the magmatic bodies. He stated that no deposits may be expected in the main batholiths where they were exposed over areas of more than 12 to 15 mi in diameter. The tops of batholiths, represented by cupolas, domes and other projections, and the nearby invaded rocks, were the favourable sites where rising hydrothermal solutions had deposited their mineral load.

A thorough critical review of the shortcomings of the magmatic hydothermal hypothesis cannot be attempted here, but a few pertinent points suggesting that magmas may not be the source of metals and gangue elements in epigenetic gold deposits can be briefly mentioned.

Many epigenetic gold deposits occur in areas where there are no observable synchronous igneous rocks from which the metals and gangue elements could have come. This is especially true in the Canadian Shield and in many other Precambrian terranes as noted by Bruce (1937*a,b*) and numerous other investigators. A similar situation exists in younger rocks in many gold belts. In most gold belts the evidence appears to indicate that the proximity of epigenetic gold deposits to exposed igneous rocks is due only to structural factors and has no genetic significance whatsoever. Perhaps this criticism is not a valid argument against the magmatic hypothesis since deep-seated igneous rocks could conceivably lie far below the roots of the deposits. For many areas such a proposition, however, is pure speculation and is 'grasping at straws' to support the hypothesis. It is more logical and more in accord with the facts to assume on the available evidence that the elements in such deposits were not derived from a magma.

It is generally considered that the metals and gangue elements were exuded from the magma during its final stages of differentiation. If we assume that the magma differentiated in the line – basic-intermediate-acid components – there is considerable difficulty on geochemical grounds in deriving elements such as copper, zinc, iron, calcium and sulphur, all of which accompany gold in its deposits, by such a process. These and many other metallic and gangue elements are enriched in basic rocks, not in acidic rocks. If there is any differentiation of such elements during magmatic processes, it is to reduce the amount of such elements toward the close of differentiation, that is during the formation of granites. Certain elements such as lead and uranium do, however, show an enrichment with differentiation and are strongly concentrated in acidic phases where they substitute in various minerals, e.g., lead in feldspars and uranium in various accessory minerals. Most of these minerals are, however, generally undersaturated with respect to lead and uranium, a feature suggesting that little if any of these elements would be drawn off in hydrothermal solutions.

A number of investigators have linked gold mineralization to gold abundance in nearby associated igneous rocks. They claim that higher (as well as lower) than background gold values in the igneous rocks indicate that gold deposits were derived from the magmas from which these rocks crystallized. The various views and arguments are summarized in Chapter II, where it was concluded that there is probably no particular relationship between the gold content of most igneous bodies such as batholiths, stocks and dykes, and nearby associated gold mineralization. Certain pyritic porphyries may be an exception to this statement, but even where these slightly auriferous rocks occur they are cut and commonly altered by the gold-bearing quartz deposits. In a recent paper Tilling *et al.* (1973) have concluded from extensive analytical data that gold becomes depleted in residual silicate melts in differentiating calc-alkalic magmas. They also observed no particular relationship between the gold content of igneous bodies and the presence of gold mineralization.

Also pertinent to the argument against magmatic hydrothermal solutions as a source for the elements in epigenetic gold deposits is the oft quoted observation that the deposits show no close time relationship to granitic or other igneous bodies, and that where the two are found together, the deposits, especially veins, cut and offset both the granitic bodies and other closely related rocks such as porphyries. This means that the granitic rocks were fully consolidated, and any process of differentiation that might have produced hydrothermal solutions had ceased when the veins were formed. Again the supposed igneous source could be sought at depth, but this is an artifice to circumvent the facts. In any event, in the writer's experience gold veins cut the igneous rocks, to which they are often said to be genetically related, down to the deepest levels of mining. Furthermore, if crystallization differentiation and formation of hydrothermal solutions is a feature of igneous rocks, one must assume on physico-chemical grounds that the outer parts of batholiths and stocks would cool first and the central parts would be the last to consolidate. The outer parts of the igneous bodies should, therefore, contain numerous hydrothermal veins, and these should increase in number and richness in gold and other metals inward and downward in the bodies. Such is not the case in nature; the central parts of batholiths and stocks are practically devoid of veins and other types of deposits in most mineralized areas.

Another similar problem for the magmatist is found in granitic bodies where several phases of granitic material, ranging from intermediate to acidic to pegmatitic composition, are present with the more acidic material being successively younger in age. These phases, in the writer's experience, show no enrichment of gold or any of the metals (molybdenum and bismuth excluded), sulphur, carbon dioxide or other volatiles with increasing acidity and youth. The pegmatites are generally devoid of gold and most sulphides (molybdenite and bismuthinite excluded) suggesting that the last extracts that gave rise to the pegmatites (assuming a magmatic origin for these bodies) were notably deficient in gold and the metallic elements common to veins. There is, therefore, a break in the lineage – granite-pegmatites-veins – which the magmatist has not yet satisfactorily answered. Could it not be that pegmatites have an origin other than by magmatic solutions? Certainly many pegmatites seem to be of metamorphic secretion origin as suggested by numerous writers since T. Sterry Hunt first postulated such an origin more than 100 years ago. Other granitic pegmatites that cut their granitic host rocks, seem to have been derived by diffusion of their constituents from the granitic rocks that were at relatively high temperature but fully crystallized and consolidated.

Another point not favouring the derivation of metals such as gold and gangue elements from magmatic hydrothermal solutions is the fact that the rocks adjacent to the supposed parent igneous bodies are not characterized by extensive hydrated, carbonated or sulphidized zones – features that should prevail if differentiation products of the igneous magmas, such as water, carbon dioxide and sulphur, were expelled outwards into the wall rocks of the stocks and batholiths. One cannot expect that all of these components would only escape up fractures or faults. On the contrary they should, when expelled, diffuse outward into the wall rocks. However, such is not the case at Yellowknife (Boyle, 1959, 1961*a*) at Keno Hill (Boyle, 1965*a*) or other localities where the writer has examined this problem carefully. If one can judge from the chemical effects in wall rocks adjacent to batholiths and stocks, it is certain that the magmas that gave rise to these rocks did not exude any quantity of volatiles, metals or gangue elements during the final stages of their differentiation.

Contact metamorphic and certain skarn bodies have frequently been quoted as evidence for the migration of metals, silica and volatiles from adjacent solidifying magmatic bodies. This could conceivably be the case in some places, but more generally it is apparent that the source of the epigenetic elements is the invaded country rocks. As suggested by the writer (Boyle, 1969*a*) these elements have moved by diffusion towards and have been precipitated in thermally and chemically active dilatant sites (usually contorted limestone beds), commonly near the borders of granitization or injected igneous bodies.

Finally, the process by which acidic and intermediate igneous rocks are formed is in considerable doubt. There are good field and physico-chemical reasons for suspecting that granite, granodiorite, monzonite and other similar rocks, which are thought to be parent sources of the constituents of epigenetic gold deposits, are not derived by igneous processes but by granitization or ultra-metamorphism. Even if magmas do arise by these more logical processes it is almost certain that they are greatly deficient in water, carbon dioxide, sulphur and the various metals such as zinc, copper, silver, gold, etc., because these elements are driven out of zones undergoing high temperature regional metamorphism early in the process, and few if any remain in any quantity in the fused materials to be differentiated at a late crystallization stage as hydrothermal solutions.

Secretion theories

General. Secretion theories, based on the assumption that the country rocks enclosing the epigenetic deposits or that lie below, above or lateral to the deposits are the source of the constituents of the epigenetic deposits, have had a long history. Agricola, writing in his famous classics, *De Ortu et Causis Subterraneorum* and *De Re Metallica* published in 1546 and 1556 respectively, concluded that veins and epigenetic lodes were deposited by circulating underground waters and reasoned that surface waters percolated downward, became heated, dissolved mineral matter, rose again and deposited this mineral matter in what he called "canales" (fissures). Agricola was, therefore, one of the first meteoric water secretionists, and it is a tribute to his genius to note that modern research has shown that certain mineral deposits, including some Tertiary gold deposits, probably originated in the manner he suggested.

More than 300 years were to pass before further progress was made in elucidating many aspects of the secretion theories. In 1885, J.G. Forchhammer, by painstaking analysis, demonstrated that ordinary rocks contain traces of many of the metals and other elements commonly found in veins. This gave a great impetus to the various secretion theories, since the presence of the metals in country rocks was held to be conclusive proof of the source of the constituents of veins and other types of epigenetic deposits. As early as 1845 K. Gustav Bischof of Bonn, the distinguished geochemist, supported the secretion theory in his *Textbook of chemical and physical geology*, and similar support can be found in the writings of G.A. Daubrée, T. Sterry Hunt, J.A. Phillips, F. Sandberger, S.F. Emmons, G.F. Becker and C.R. Van Hise during the latter half of the 19th century and the early part of the present century. All of these investigators ascribed the source of the metals in veins to the country rocks containing them but differed in their opinion as to whether ascending or descending meteoric water was the responsible transporting medium. Of all these investigators R. Daintree, writing in his *Geology of the Ballan District, Victoria, 1866*, seems to have appreciated the geochemical cycle of gold most clearly and its importance in the formation of gold-quartz reefs. He said: "I had long come to the conclusion that most, if not all, the gold in the quartz reefs was derived from the rocks in which these reefs occur. That the strata themselves received their supply of gold at the period of their deposition from the ocean in which they were deposited. That the organic matter and the gases generated therefrom on decomposition, sulphuretted hydrogen, etc. were the cause of the precipitation; and that the amount of metallic deposit was in proportion to the amount of organic matter deposited with the organic sediment."

The secretion theories enjoyed considerable popularity in Europe and in America during the latter part of the 19th century but were strongly opposed during its closing years by A.W. Stelzner of Freiberg, F. Pošepný of Przibram, J.R. Don of Otago and L. De Launay of Paris. These investigators were the first advocates of the magmatic hydrothermal theory. They demonstrated that the metals could not have come from the rocks immediately adjacent to veins as F. Sandberger had suggested in his restricted lateral secretion theory, but they drew the entirely erroneous conclusion that the metals in the country rocks were all introduced from the fissures and faults in which the veins occur. They, therefore, failed to appreciate the painstaking analytical work of Bischof, Forchhammer and Sandberger and the important geochemical considerations bearing on the migration and concentration of the elements, such as precipitation of various metals during sedimentation processes, elucidated by Sterry Hunt.

During the first 50 years of the 20th century the magmatic hydrothermal theory gained in popularity, and secretion theories were practically forgotten. Nearly all epigenetic gold deposits known up to 1950 were, therefore explained in terms of the hydrothermal theory. Since 1950, the major advances in geochemistry and in our knowledge of the migration and concentration of the elements have caused many to question this theory, and one now sees a decided swing of the pendulum of thought toward secretion theories for the origin of many epigenetic gold deposits.

The secretion theories of the origin of epigenetic deposits embrace a number of concepts and mechanisms. Some of these are briefly outlined below with some general criticisms; the details of the mechanisms are described and discussed subsequently.

Meteoric water secretion theories. Most of the early investigators considered meteoric water, either descending or ascending or both, to be the collecting and transporting medium for the metals, sulphides and gangue minerals found in epigenetic deposits. The source of these constituents was considered by most geologists to be the local rocks in the general vicinity of the deposits; Sandberger (1882–1885), however, concluded from his analytical researches that the vein elements were derived from the wall rocks immediately adjacent to the veins. This view is in general incorrect, but as we shall see later, many of the metals and compounds found in gold-bearing veins and lodes, such as Fe, Ca, Mg and SiO_2 may have been derived under certain conditions from the adjacent wall rocks.

Recent research utilizing $^{18}O/^{16}O$, D/H and other isotopic ratios strongly suggests that gold deposition in many of the Tertiary and younger deposits took place essentially from meteoric water (including in places sea water) set into convective circulation by interaction with rising igneous intrusions. Examples are widespread including Tonopah, Goldfield and Comstock Lode, Nevada (Taylor, 1973); Bodie, California and elsewhere (O'Neil *et al.*, 1973; O'Neil and Silberman, 1974); Creede, Colorado (Bethke *et al.*, 1973); Sunnyside Mine, Eureka mining district, San Juan County Colorado (Casadevall, 1976); Tui Mine, Hauraki goldfield, New Zealand (Robinson, 1974); Kurokô deposits, Japan (Sakai and Matsubaya, 1974; Ohmoto and Rye, 1974); and epithermal Au-Ag districts, United States (White, 1974). There is evidence that some of the epithermal gold deposits in the northeastern U.S.S.R. had a component of meteoric water (with dissolved air) in the solutions from which they were precipitated. This is surmised from the work of Goncharov and Shugurova (1973), who studied the gaseous composition of gas-liquid inclusions in the constituent minerals. They found a ratio for O/N = 0.25–0.26, approximately equal to that in the atmosphere (0.27). From this they concluded that atmosphere constituents played a part in the origin of these deposits. In general, therefore, it appears that meteoric waters have dominated during mineralization processes in epithermal gold-silver belts, but some investigators consider that magmatic water also played a part (Robinson, 1974; O'Neil and Silberman, 1974; White, 1974) or was entirely responsible for the precipitation of gold as in the Tertiary Megradzorsk gold deposits in Armenian S.S.R. (Akopyan *et al.*, 1976). It has never been clear to the writer how one can isotopically characterize magmatic water from metamorphic water sweated out of the rocks. Until this problem is resolved the term 'magmatic water' should remain in abeyance.

While the source of the water seems at least partly solved, there still remain problems with respect to the source of the base metals, sulphur, gold and silver. Some investigators have concluded that the magmas with which the meteoric water has interacted are the most reasonable source; others consider the volcanic sedimentary pile or the underlying basement rocks more likely sources. The last two appear more probable. In passing it is interesting to note that the so-called epithermal deposits were those with which the early meteoric water secretionists were most familiar.

While meteoric water seems the most probable medium of transport for gold and other elements in what are called epithermal or near-surface deposits, the situation may be different for deep-seated, high-temperature deposits. In their formation, if water was involved as a collecting and transporting medium, it was probably mainly derived by dehydration of minerals such as micas, etc. during metamorphism (metamorphic water).

Metamorphic secretion theories. Metamorphic secretion theories as applied to epigenetic gold deposits assume that the gold, silver and gangue elements, initially present in the country rocks, were mobilized and concentrated in available faults, shear zones, fractures and chemical traps (carbonate rocks) during metamorphic events. There are many variations on this theme, some of which are discussed subsequently. In recent years many gold deposits have been explained by metamorphic secretion theories.

Boyle (1955,1959,1961*a*) and Wanless *et al.* (1960) explained the Yellowknife gold-quartz deposits in Precambrian greenstones and (greywacke-slate) sediments in terms of mobilization, migration and concentration of elements during regional metamorphic events involving granitization. The gold-quartz deposits in the argillite-graphitic schist-quartzite terrane of the Yukon Group in the Keno Hill area, Yukon were explained in a similar manner (Boyle, 1965*a*), as were also the gold-quartz deposits in the slate-greywacke-quartzite assemblage of the Meguma Group in Nova Scotia (Boyle, 1966). The papers on the Yellowknife deposits have been criticized by Ames (1962) and McConnell (1964*a*), who claim that the data presented favour a hydrothermal origin. Replies to the criticisms have been published (Boyle, 1964; Boyle *et al.*, 1963*b*).

In 1953 Knight (1957) postulated the "source bed concept" for the origin of sulphide orebodies. By this he suggested "that all sulfide orebodies of the majority of fields are derived from sulfides that were deposited syngenetically at one particular horizon of the sedimentary basin constituting the field, and that the sulfides subsequently migrated in varying degree under the influence of rise in temperature of the rock environment." He gave a few examples of auriferous deposits (Rand, Canadian Shield) whose origin he thought was encompassed by the concept.

Nifontov (1957) attributes a number of the gold-quartz deposits of U.S.S.R. to metamorphic processes, especially those occurring in sedimentary rocks. Chaikovskii (1963) and Badalov (1965*b*, 1966) have, likewise, stated that the gold in some of the deposits of U.S.S.R. was extracted from the country rocks.

Davies (1963,1964) studied a number of gold deposits in the Rice Lake–Wanipigow River area of Manitoba and concluded that the concentration of gold is due to a redistribution or diffusion and migration of the element in the country rocks into fractures, faults and shear zone in zones of lower grade metamorphism. This view is corroborated by the work of Stephenson (1971) and Stephenson and Ehmann (1971) in the same area.

Moiseenko and co-workers attach considerable importance to the processes of metamorphism in the formation of gold deposits. In a series of papers, Moiseenko (1965), Moiseenko *et al.* (1970), Shcheka and Moiseenko (1970), Moiseenko and Fat'yanov (1972) and Moiseenko and Neronskii (1973) reached the general conclusion that the primary sources of gold in the earth's crust are basic and ultrabasic magmatic rocks in which the element is present in a dispersed form. During granitization and metamorphism gold is released, is transferred to melts or solutions, migrates, and is deposited in local tectonic structures. Repeated mobilization and deposition of gold is frequently necessary for the formation of economic epigenetic gold deposits according to these investigators.

Shcherbakov (1967,1970) considers that the source of gold in endogenous deposits may be basaltic magma, granitoid magma resulting mainly from the fusion of sedimentary rocks or volcanic-sedimentary piles from which the gold is mobilized during hydrothermal metamorphism and collected in local structures such as faults and fractures. Buryak (1967*a*; 1975*a*) and Buryak *et al.* (1972) also considered that gold was mobilized during metamorphic and granitization events. During these processes in the Vitim-Patom Upland in particular gold was decreased in amount as the rocks passed from shales to gneisses to granitic rocks. The authors calculated that the loss of gold during metamorphism and granitization processes amounted to 3.3 tons/km^3.

Metamorphic secretion theories have been favoured in recent years as an explanation of the origin of epigenetic gold deposits in Precambrian terranes comprising greenstones, iron-formations and metasediments. Anhaeusser *et al.* (1969), Vilijoen *et al.* (1969,1970) and Anhaeusser (1976) consider that the gold in the deposits of the greenstone belts of southern Africa (Barberton Mountain Land, Rhodesia, etc.) and elsewhere was initially present in the mafic and ultramafic lavas and associated sediments and was mobilized and concentrated in dilatant zones during metamorphic events attendant upon granitic intrusion. In a more recent paper Saager (1973) advances a similar origin for epigenetic gold deposits in Precambrian rocks and suggests that the ultimate source of the gold in the vein deposits of the Swaziland greenstone belts is the 'primitive' peridotitic and basaltic komatiites of the Onverwacht Group rather than the intruding granites. The komatiites are relatively rich in gold (0.02 ppm). In more recent papers Anhaeusser *et al.* (1975) and Anhaeusser (1976) note that the komatiites contain from 0.001 to 0.0015 ppm, a value substantially lower than the worldwide tholeiite average of 0.0025. They think two interpretations of these new data are possible. One is that these are primary concentrations, and the other is that the lavas contained significantly higher amounts of gold, but that later metamorphism and hydrothermal activity has erased all record of this fact. Judging from the petrographic data available on these rocks and from the data of numerous studies in U.S.S.R., the latter appears most probable. For the Kirkland Lake–Larder Lake deposits in Ontario, Ridler (1970) has postulated a syngenetic-metamorphic origin for the gold deposits, the gold being derived mainly from iron-formation. Belevtsev (1970) considers that the source of the metals in a number of Precambrian deposits is the host rocks and thinks that they were mobilized and concentrated mainly by the action of metamorphism aided greatly by metamorphic water. The gold-quartz bodies in the greenstones of the Ramagiri goldfield in Andhra Pradesh, India have been similarly explained by Ghosh *et al.* (1970), but their metamorphogenic origin has been questioned by Rao and Srinivasan (1971), who consider the veins to be typically hydrothermal, controlled by structures and tectonism. Iyer (1970), however, considers these veins and others in the greenstone belts of southeast Mysore to be of metamorphic secretion origin. Deposits in other Precambrian terranes have also been explained by metamorphic secretion theories. Here we may mention the Kalgoorlie goldfield in Western Australia (Travis *et al.*, 1971); the Ashanti Gold Mine, Obuasi, Ghana (Wilson, 1971); the Kilo-Moto deposits, district of Mongbwalu, Zaire (Lavreau, 1973); the Homestake deposit, South Dakota (Sawkins and Rye, 1971,1974; Rye and Rye, 1972; Rye *et al.*, 1974*a*); and Precambrian gold deposits in general (Henley, 1971).

A number of deposits of variable age and type have been explained by metamorphic secretion, remobilization or regeneration theories in recent years. Morávek and Rus (1970) consider that the quartz-carbonate veins enriched in gold, uranium and selenium in the Sedlcany-Krásná Hora area of Czechoslovakia owe their origin to regeneration or remobilization of gold from earlier auriferous veins in Variscan deposits associated with the Central Bohemian pluton. At Tilkerode, Harz Mountains, Germany, Tischendorf (1970) has shown that a number of the elements in the carbonate-hematite gold selenide vein were mobilized and concentrated from the country rock. The specific mobility of the elements in decreasing order was found to be as follows: S, Mo, Cu, Se, Co, Au, Ni, V, Zn, Pb, Cr and Sn. Keays and Kirkland (1972) found that gold was leached during alteration of the Thomson River dyke, Victoria, Australia. The dyke was originally an ultramafic differentiate with segregated copper-nickel sulphides. The leaching of the gold and its redeposition in quartz stringers with chalcopyrite and/or pyrite in a nearby dilatant zone took place mainly during faulting, shearing and extensive alteration by carbonate-bearing solutions. The extraction of the gold from the pre-existing sulphides in the ultrabasic body is clear as shown by depletion haloes of gold about the orebody. The platinoids, on the other hand, were not affected to the same extent as the gold. In the Urals gold province Zhelobov (1972) suggests that the gold is extracted from ultramafic rocks by granitization and magmatic assimilation processes along deep-seated fault systems, and Vilor and Sarapulova (1971) consider that epigenetic gold deposits in general are derived mainly from sedimentary rocks, the gold in these rocks being leached out during progressive metamorphism and redeposited in fractures and faults under conditions of changed pressure and temperature. Even crystallized granitoids may be a source of gold. Anoshin and Potap'yev (1966) found that the element is lost from granitoids that are metamorphosed or hydrothermally altered. They postulated that the gold so lost is concentrated in quartz veins. Shcherbakov *et al.* (1973) examined the gold content of granites and other rocks and their accessory magnetites in the Altai-Sayan gold belt. Intensive redistribution of gold was noted in the regions of hydrothermal metamorphism from which they concluded that much gold was leached from these parts. Belyaev *et al.* (1972) are of the opinion that metamorphic processes are responsible for the gold-sulphide mineralization in the amphibolites in the Olenii Ridge Lower Proterozoic sedimentary-volcanic formations, U.S.S.R.

In a recent contribution on the Kalgoorlie goldfield, Western Australia, Tomich (1974) postulates that the Golden Mile is an Archean volcanogenic-type deposit, modified and redistributed along later developed structures.

Li and Shokhina (1974*a*, *b*) demonstrated that the initial gold content in the rocks of the Yenisey Range is not changed substantially during regional metamorphism either in the low temperature greenschist and epidote-amphibolite facies or in the high temperature amphibolite and granulite facies. Radical changes in mineral composition under the conditions of high temperature metamorphism are, however, accompanied by redistribution and dispersion of gold within the rocks. Mushkin *et al.* (1974) think that the source of gold in metamorphic terranes is due to eclogitization processes operating in the lower part of the crust. These processes are attended by release of Si, Na, K and Au (~ 0.015 g/m^3). They drew this conclusion from their study of the eclogitization of gneisses in the granulite facies of the southern Tien-Shan.

In a more recent contribution Moore (1975) ascribes the origin of the Proterozoic gold deposits of the Saudi Arabian Shield to mobilization of the gold from the country rocks and concentration in suitable structures during the period of regional metamorphism. Similarly Pyke (1975,1976), noting that many of the gold deposits in the Timmins (Porcupine) area of Ontario show a close spatial relationship of Archean ultramafic metavolcanics, has postulated that these rocks are the principal source of gold in the deposits, and that the gold was extracted from them and concentrated in dilatant zones through a process of lateral secretion when the area was subjected to dynamothermal metamorphism and the ultramafic volcanics suffered extensive carbonatization. Hutchinson (1975) has also advocated a metamorphic secretion theory for the origin of Precambrian and Phanerozoic lode gold deposits. He postulates that initially the gold was deposited in sulphide bearing interflow sediments (iron-formations and tuffs) in eugeosynclinal volcanic terranes, the metal being subsequently concentrated, probably by lateral secretion, in lodes, veins and stockworks, as a result of deformation, recrystallization and redistribution during later metamorphism.

Roslyakova and Roslyakov (1975) document numerous researches in U.S.S.R. where it is evident that most, if not all, of the gold in epigenetic deposits has come from country rocks by processes of metamorphism or hydrothermal activity. Most of these researches have already been mentioned in the text above; one by A.T. Bendik, not available to the writer, is of interest. Bendik claims that the gold in the great Muruntau deposits in Uzbek S.S.R. was initially present in the sedimentary host rocks (carbonaceous siltstones and sandstones) and was mobilized and concentrated as a result of hydrothermal metamorphism. Badalov *et al.* (*in* Petrovskaya, 1974) remark that in the Almalyk auriferous region metasomatism of middle-upper Paleozoic effusive-intrusive complexes has liberated large amounts of silica and suggest that the ubiquitous coincident occurrence of gold and silica (quartz) indicates that both were derived from the same source.

A study of the sulphur isotopes in the auriferous Wood's Point dyke swarm, Victoria, Australia (Fig. 53) by Green and Keays (1976) suggests that the bulk of the sulphides associated with the gold could not have been derived from the adjacent sedimentary country rocks or from the copper-nickel sulphides in the dykes. The more mafic dyke bulges, copper-nickel sulphides and gold mineralization are all concentrated along two lineations paralleling the fold axes of the host sediments. Green and Keays considered that these lineations may represent deepseated fractures that controlled the upward migration of gold-bearing hydrothermal solutions from depth. The source of the gold, they thought, could have been various rock types present at depth, including copper-nickel sulphides and Lower Paleozoic sediments.

An investigation of the gold distribution and foliation development in the Lower Paleozoic rocks of central Victoria, Australia and its bearing on gold mineralization by Glasson (1975) has shown that one possible source for gold is the black pyritic Cambrian shales whose gold contents (av. 0.068 ppm) are well above those of the greywacke, quartzite and other sediments (av. 0.003 ppm). Furthermore, during foliation development within the Clunes goldfield, pyrite and other minerals such as albite are dissolved and their constituents rearranged. During this rearrangement Glasson considered that some of the constituents of the pyrite and other minerals, including gold, may have contributed to the filling of the gold-quartz reefs.

Henley *et al.* (1976) and C.J. Paterson (pers. commun., 1976) have made an extensive study of the gold-quartz and scheelite-gold-quartz lodes in the Mesozoic Haast Schist, Central Otago, New Zealand. They have concluded that the source of the elements are rocks deep in the schist pile, and that during metamorphism, uplift and hydraulic fracturing gold, tungsten and their accompanying elements were concentrated in available fractures and faults. There is an interesting historical summary in the publication by Williams (1974) of the various genetic theories of origin of the auriferous Otago lodes; these range from meteoritic water secretion to magmatic hydrothermal theories.

Few younger (Tertiary) deposits associated with volcanism have been examined carefully from the viewpoint of secretion theories. In the old literature, Becker (1882) claimed that the hard, fresh undecomposed diabase (andesite) hosting the Comstock Lode contained twice as much gold and silver as the highly altered (propylitized) rocks in the immediate vicinity of the lode. From these data he drew the conclusion that the filling of the lode was by lateral secretion, the precious metals and the gangue being derived essentially from the propylitized rocks. The same idea was held by B. von Inkey, F.W. Hutton, J.M. Maclaren and others for the origin of the Hauraki gold-quartz veins (Finlayson, 1909; Williams, 1974), although later investigators, including J.R. Don, A.M. Finlayson and W. Lindgren, considered the auriferous deposits to be of magmatic hydrothermal origin.

In the more recent literature lateral secretion theories have again been considered. De Roever and Lodder (1967) postulate that the Rodalquilar deposits in Almeria, southeastern Spain are of syngenetic origin. The deposits are veins, consisting mainly of banded fine-grained quartz and alunite, some pyrite, marcasite, pyrrhotite, covellite, delafossite, jarosite, hematite, geothite and native gold, in highly altered ignimbrites of Neogene age. De Roever and Lodder consider that gold-bearing volatiles emanated from the ignimbritic materials and deposited their gold along the walls of fumaroles. The deposits are, therefore, fossil fumaroles that are enriched in gold.

At Guanajuato, Mexico, Gross (1975) attributes the source of vein materials in the gold-silver deposits in the Sierra, Veta Madre and La Luz fault systems to the underlying Mesozoic sedimentary rocks. Alkaline groundwater in the rocks was heated to temperatures above 350°C during the period of volcanism in the middle Oligocene. The hot solutions leached vein-forming materials from the surrounding rocks and escaped along faults formed by crustal subsidence following volcanism. The solutions moved upward along the faults, and the deposition of vein material during the upper Oligocene was caused primarily by a decrease in temperature estimated to be approximately 10°C/100m.

Casadevall (1976) and Casadevall and Ohmoto (1977) have made an extensive study of the Sunnyside Mine, Eureka mining district, San Juan County, Colorado by means of fluid inclusions and various isotopes. The gold and base metal ores are of Miocene age (13.0–16.6 m.y ago) and are localized in faults and fracture fillings associated with the San Juan–Uncompahgre calderas. Sulphur isotope studies suggest that the source of the sulfur in the ores was upper Paleozoic marine evaporites; isotopic studies of lead and rubidium-strontium indicate that the metals in the ores were scavenged from both Tertiary volcanic rocks and the underlying Precambrian basement rocks. The hydrothermal fluids were predominantly deep circulating meteoric water.

Capacity of country rocks to supply gold

The gold content of most rock types is discussed in considerable detail in Chapter II, and the average gold content of 1 mi^3 and 1 km^3 of several common rock types is shown in Table 71. It is immediately apparent that practically all rock types are adequate sources of gold for concentration in most types of auriferous deposits. Among the igneous rocks those of ultrabasic and basic character followed by the intermediate types contain the most gold. This may partly account for the marked frequency of gold deposits in greenstone and propylitic belts originally constituted of ultrabasic flows and sills, basalts, andesites, dacites, etc. It may also explain why in auriferous belts there is often an association of gold deposits with highly altered (serpentinized and carbonated) ultrabasic bodies. Among the various clastic sedimentary rocks the sandstones and conglomerates hold the most gold followed by the greywackes and subgreywackes. Again there is a correlation of the frequency of occurrence of auriferous deposits with types of rocks, the metamorphosed greywacke-sandstone terranes in many parts of the world being characterized by the presence of numerous gold-quartz veins, saddle reefs, etc. Further correlations are evident with respect to auriferous deposits and the presence of the relatively gold-rich sulphidic schists and pyritic slates. Metamorphosed volcanic and sedimentary terranes containing such rocks are frequent hosts for various types of gold deposits.

Mechanisms of migration and concentration of gold in secretion theories

General. Secretion of gold from the country rocks and its deposition in structural traps such as faults, fractures and shear zones or in chemical traps, mainly carbonate beds, involves various mechanisms for the mobilization, migration and concentration of the element. Few of these are clearly understood in a physicochemical sense since it is practically impossible to experiment on the scale necessary to elucidate the mechanisms.

One can assume on reasonably good grounds (*see* Chapter II) that much of the gold in the common rocks is present in pyrite with smaller amounts in magnetite and various other minerals. There is probably also an interstitial component of the element loosely bound in an unknown manner along the grain boundaries of the rock and along various other structural

Table 71. Gold content of a cubic mile and cubic kilometre of various types of igneous and sedimentary rocks*

Rock type (Gold content in ppm in brackets)		Gold content/mi^3		Gold content/km^3	
		(g x 10^6)	(oz x 10^6)	(g x 10^6)	(oz x 10^6)
Igneous type rocks					
Ultrabasic	(0.0045)	56.273	1.809	13.500	0.434
Basic	(0.0072)	90.036	2.895	21.600	0.694
Intermediate	(0.0047)	58.774	1.890	14.100	0.453
Acid	(0.0027)	33.764	1.086	8.100	0.260
Sedimentary rocks					
Sandstone, arkose, conglomerate, etc.	(0.0263)	328.882	10.574	78.900	2.537
Shale, mudstone, argillite, etc.	(0.0039)	48.770	1.568	11.700	0.376
Sulphidic schists, pyritic black shale, etc.	(0.0143)	178.822	5.749	42.900	1.379
Tuffs	(0.0023)	28.762	0.925	6.900	0.222
Limestone, dolomite	(0.0034)	42.517	1.367	10.200	0.328
Greywacke and subgreywacke	(0.0076)	95.03	3.055	22.800	0.733

*Data compiled from Tables 13 and 15.

discontinuities such as microfractures. When a pile of rocks with gold so disposed is subjected to the conditions of regional metamorphism (P = 10kbar; T = 500°C) or affected by intrusion of igneous bodies a great variety of complex reactions take place. None of these are known in any detail, but it is reasonable to assume that water and other volatiles, silica and the various metals such as Cu, Pb, Zn, Ag and Au are mobilized. That this is the case is readily shown by heating powdered pyritiferous shales or volcanic rocks in a current of steam and condensing the effluent in a cold trap. Experiments such as this were carried out more than 70 years ago by Gautier and others in their researches on gases in rocks (Clarke, 1924). They have been recently revived by Walker and Buchanan (1969), who obtained a highly reactive gaseous mixture when black shale was heated at temperatures ranging from 300 to 400°C. They considered that the gaseous mixture, which included H_2O, HCl, CO_2, CH_4, H_2S, S_2 and higher polymers, is likely to be important in the transport of the metals.

Similar experiments by Belevtsev *et al.* (1972), utilizing various aqueous acid, neutral and alkaline solutions to leach rocks at 300°C and 300 atm, showed that both the ore and petrogenic elements pass into solution rather readily especially from unmetamorphosed sedimentary rocks. When the rocks are metamorphosed (e.g., gneisses) removal of the various elements is more difficult and restricted. Details should be sought in the original publication. The authors concluded that the experimental data confirm the great mobility of ore- and rock-forming elements during metamorphism and ultrametamorphism.

Once released from its bonded sites in rocks gold may migrate either by mass transport, diffusion or a combination of both mechanisms. Movement by mass transport generally involves solution of the gold in liquid or gaseous water, migration of the solution or gas along structural discontinuities such as fractures, faults and shear zones and precipitation in favourable sites as a result of various chemical interactions or a decrease in temperature and/or pressure in the system. The various modes of solution and precipitation of gold in aqueous solutions and gases are discussed in Chapter II and need not be repeated. It is easy to visualize a model in which gold and its associated gangue elements follow the consecutive courses; dissolution (mobilization) from deeply buried rocks under high temperature and pressure, migration of the gold and other elements in solution upward along a fault system under a driving gas pressure and precipitation of the quartz, sulphides and gold in dilatant zones in a region where the temperature and pressure are greatly reduced compared with that where the gold was dissolved (mobilized). Such a model is applicable in a number of auriferous belts, particularly those where the deposits were formed near the surface as in certain Tertiary terranes. For deposits formed under deep-seated conditions, as in Precambrian terranes, such a model is not applicable or is applicable only in a restricted sense. Under these conditions diffusion processes are more probable.

Diffusion is the spontaneous statistical process whereby atoms, ions and molecules migrate through rocks, natural solutions and gases, as a result of differences in free energy (chemical potential) between any two points in these media. Since diffusion is essentially dependent on the kinetic properties of atoms, ions and molecules the nature of the binding of the medium through which diffusion takes place largely determines the rate. In gases diffusion is rapid because the mean free path, which is equivalent to the average distance between atomic, ionic or molecular collisions, is long. In liquids it is short and diffusion is less rapid, and in solids it is very short resulting in slow rates. Increase of temperature and pressure respectively increase and decrease the rates in all media. Shearing, however, increases the rates in solids.

In rocks diffusion may take place in the following ways:

1. Migration of constituents (SiO_2, CO_2, H_2O, S, As, Cu, Ag, Au, etc.) in a gaseous state or as ions and molecules along grain boundaries and fractures and through pores and other discontinuities in rocks. The migration is accomplished in part by surface diffusion, but where gases are involved there may also be some mass transport. This mechanism is probably operative in regional metamorphism, formation of skarn deposits and other relatively high temperature phenomena. It has been suggested by the writer (Boyle, 1959, 1961*a*, p. 94) as an explanation for the distribution of various volatiles in the regional metamorphic zonation in the Yellowknife gold belt, Northwest Territories. Confirmation of the process seems evident from sulphur isotopic data (Wanless, *et al.,* 1960).

2. Migration of ions, hydrated ions and molecules through a relatively stationary water gas or other natural gas such as carbon dioxide that pervades the grain boundaries, pores and other discontinuities in rocks. This mechanism is likewise a relatively high temperature phenomenon. Various constituents such as SiO_2, K, Na, Zn, Cu, Ag, Au, Fe, etc. may be transferred in this manner judging from the data of Morey (1957). The writer (Boyle, 1955, 1961*a*, p. 94, 120, 136) has explained the metamorphic zonation and the transfer of silica and other constituents in the wall-rock alteration zones of the gold-quartz veins and lenses at Yellowknife by this mechanism. Confirmation seems evident from sulphur isotopic data (Wanless *et al.*, 1960).

3. Migration of ions, hydrated ions and molecules through stationary water that occupies all fractures, breccia zones, pores and other discontinuities in rocks. Many near-surface gold veins in (Tertiary) volcanic terranes probably owe their origin to this mechanism. Support for this mechanism is found in the remarks by Ewers (1969) with respect to the diffusion of gold and the constituents of quartz and pyrite through stationary solutions during hydrothermal experiments.

4. Diffusion of ions, atoms and molecules through the crystal lattices of the constituent minerals of rocks. At low temperatures the rate is extremely slow. At high temperatures and where the crystal lattices are under shear the rate is greatly increased. This mechanism is probably operative in the formation of gold-bearing contact metamorphic deposits, in certain shear zone deposits and in the formation of high temperature gold-quartz veins in intensely metamorphosed rocks.

The mechanisms of formation of epigenetic gold deposits appear to have differed little with time, the processes that gave rise to Precambrian deposits recurring throughout successive geological eras. An outline of the mechanisms thought to have operated in the formation of Precambrian deposits can, therefore, serve, with modifications, as a basis for the discussions on the formation of deposits in the Paleozoic, Mesozoic and Cenozoic eras.

Precambrian (mainly Archean) deposits occur principally in volcanic or sedimentary terranes or in granitic bodies that invade the volcanics or sediments. Most of the deposits in volcanic terranes are localized in faults, fractures or shear (schist) zones and comprise quartz veins and lenses, stockworks, or pyritized and silicified bodies of rock usually enveloped by extensive alteration zones marked by chloritization, carbonatization, pyritization and sericitization. Deposits in sedimentary terranes are mainly quartz veins and lenses, saddles or irregular bodies developed along bedding planes, in drag folds, or in local shears and faults. Wall-rock alteration effects are absent or minimal. Deposits in granitic rocks are commonly veins, stockworks or pyritized and silicified bodies that may or may not be accompanied by marked alteration zones.

There are a number of features in gold-bearing Precambrian greenstone belts that have a direct bearing on the origin of the gold deposits in these belts. Most of these have been mentioned previously in various parts of the text and will now be summarized briefly.

Most greenstone belts are composed essentially of basalts, andesites, dacites, gabbroic-dioritic intrusive plugs and dykes and subsidiary rhyolite. Ultrabasic flows and intrusive plugs and dykes are generally local. None of these rocks are particularly enriched in gold – the initial average for the rocks of greenstone piles probably being about 0.007 ppm (*see* Table 13). Within greenstone belts, however, there are usually three other rock types that are commonly enriched in gold (and silver). These include various sulphide schists, iron-formations and pyritiferous quartz-feldspar porphyry dykes and bosses. These rocks vary widely in their gold (and silver) contents as shown in Tables 13, 15 and 16. A general average for these rocks of 0.02 ppm seems reasonable. Such rocks were probably the main source of the gold that has been concentrated in epigenetic deposits in greenstone belts, although the volcanics and basic and ultrabasic intrusives may have made sizeable contributions as we shall see later.

All Precambrian greenstone belts have been folded, extensively metamorphosed, granitized and/or injected by granitic bodies. Contemporaneous with these events, and in places somewhat later, the rocks have been extensively faulted and sheared. During these processes at least three mechanisms could conceivably have given rise to epigenetic gold deposits.

The first mechanism for consideration involves granitization of enormous volumes of volcanic rocks and their associated sediments. During this process large amounts of volatiles (H_2O, CO_2, S, etc.) and metals, including gold and silver, originally present in the volcanic pile may possibly have been dissolved in the resultant granitic melt, which upon cooling and crystallizing ejected solutions containing silica, volatiles, gold, etc., and these found their way into available fractures, faults and shear zones where they were partitioned and ultimately crystallized as quartz, carbonates, pyrite, arsenopyrite, gold and other minerals.

There can be little doubt that granitization of volcanic piles releases vast quantities of volatiles and metals, as can be readily seen by comparing the average contents of the rocks before and after granitization (Table 72). When one considers that most Precambrian greenstone belts have been granitized over many miles, and hence that many cubic miles of rock have been transformed, there is no need to look further than the volcanic piles of rocks for the source of the gold and its associated elements. An estimate by the writer of the gold that could have been released by granitization of the Yellowknife greenstone belt amounts to some 30 million oz.

This attractive hypothesis has, however, a number of defects from a chemical and thermodynamic viewpoint. Chief among these is the production of silica (quartz) one of the most abundant components of practically all types of epigenetic gold deposits. During granitization of intermediate and basic volcanic rocks silica is required in considerable amounts at the sites of transformation as shown by analyses of rocks in granitized sequences (Boyle, 1961*a*, p. 72). This precludes the possibility of excess amounts of silica at the end stages of granitization in the writer's opinion. Another flaw in the hypothesis is the thermodynamic argument of the apparent impossibility of retaining the volatiles (the carriers of the metals) in magmatic melts during the granitization process. Since the system involved in granitization is invariably open, the volatiles and hence the metals will migrate by diffusion away from the sites of transformation mainly during the early stages of the process, not at the end stages. Profiles of volatiles outward from the centres of granitization suggest that this is indeed the case (Boyle, 1961*a*, p. 85).

Because the granitization process, as envisioned with a final magmatic phase differentiating volatiles and metals, appears improbable the writer has suggested a granitization-metamorphic-dilation mechanism for the origin of gold deposits in Precambrian volcanic belts (Boyle, 1961*a*). The essentials of this mechanism can be described as follows.

During the orogenic events, which gave rise first to complex folding and then granitization of volcanic piles and associated sediments, marked temperature gradients existed outward from the foci of granitization leading to the formation of the zone facies of metamorphism in greenstone belts. At this time much water, carbon dioxide, sulphur and probably some of the chalcophile elements were mobilized and migrated toward the cooler parts, that is, down the temperature gradient at right angles to the isothermal lines as shown by the vectors in Figure 91*a*.

If no structural breaks were formed in the rocks, the result would be a simple metamorphic halo about a granitized centre. Such unmineralized belts occur in some Precambrian terranes. In many belts, however, great systems of faults and shear zones were formed near the end of the orogeny and formation of the granitic bodies. As a consequence of these structural events the migration vectors were radically changed by the dilatancy of the shear zones as shown by Figure 91*b*. The shear zones literally sucked the mobile carbon dioxide, water, sulphur and other elements from the country rocks and channelled them toward the surface. Because of the great extent and depth of most of the shear zone and fault systems the effects of dilatancy were felt over great volumes of the country rocks, and mobile elements were probably contributed from points thousands of feet horizontally and vertically from the shear-zone and fault systems. Extensive structures

Table 72. Gain or loss of volatiles and metals during granitization of a cubic mile and cubic kilometre of greenstone belts, sedimentary belts and ultrabasic rocks

Constituent	H_2O	CO_2	S	As	Sb	Cu	Pb	Zn	Ni	Co	Cr	Au	Ag
		(%)						(ppm)					
Content in volcanic (greenstone) belts prior to granitization	1.80	0.262	0.094	7.0	1.0	80	6	93	123	50	240	0.007	0.12
Content in derived granodiorite rocks	0.97	0.084	0.024	2.0	0.2	10	12	55	10	5	5	0.003	0.05
Gain (+) or loss (–) in short tons (or troy ounces) X10⁶ during transformation of a cubic mile of greenstone rocks to granodiorite*	–114.4	–24.5	–9.65	–0.069	–0.011	–0.965	+0.082	–0.524	–1.558	–0.620	–3.239	–1.608 (oz)	–28.14 (oz)
	(–24.9)	(–5.34)	(–2.1)	(–0.015)	(–0.0024)	(–0.210)	(+0.018)	(–0.114)	(–0.339)	(–0.135)	(–0.705)	(–12.0g)	(–210.g)
Content in pelitic (greywacke and slate) sedimentary belts prior to granitization	3.13	0.30	0.250	20	1.0	65	15	110	70	26	135	0.012	0.20
Content in derived granitic rocks	0.97	0.084	0.024	2.0	0.2	10	12	55	10	5	5	0.003	0.05
Gain (+) or loss(–) in short tons (or troy ounces) X10⁶ during transformation of a cubic mile of pelitic rocks to granite†	–297.7	–29.77	–31.15	–0.248	–0.011	–0.758	–0.041	–0.758	–0.827	–0.289	–1.792	–3.618 (oz)	–60.32 (oz)
	(–64.8)	(–6.48)	(–6.78)	(–0.054)	(–0.0024)	(–0.165)	(–0.009)	(–0.165)	(–0.180)	(–0.063)	(–0.390)	(–27.0g)	(–450.0g)
Content in ultrabasic rocks prior to granitization	7.80	0.67	0.047	4.0	0.4	80	4	97	1285	135	2000	0.005	0.08
Content in derived granodiorite rocks	0.97	0.084	0.024	2.0	0.2	10	12	55	10	5	5	0.003	0.05
Gain (+) or loss (–) in short tons (or troy ounces) X10⁶ during transformation of a cubic mile of ultrabasic rocks to granodiorite‡	–941.46	–80.78	–3.170	–0.028	–0.003	–0.965	+0.110	–0.579	–17.575	–1.792	–27.500	–0.80 (oz)	–12.06 (oz)
	(–204.9)	(–17.58)	(–0.690)	(–0.006)	(–0.0006)	(–0.210)	(+0.024)	(–0.126)	(–3.825)	(–0.390)	(–5.985)	(–6.0g)	(–90.0g)

*Numbers in parentheses refer to metric tons or grams X10⁶ gained or lost during transformation of a cubic kilometre of greenstone rocks to granodiorite.

†Numbers in parentheses refer to metric tons or grams X10⁶ gained or lost during transformation of a cubic kilometre of pelitic rocks to granite.

‡Numbers in parentheses refer to metric tons or grams X10⁶ gained or lost during transformation of a cubic kilometre of ultrabasic rocks to granodiorite.

that impose such marked dilatant effects on the country rocks may be termed 'first-degree' dilatant zones.

During the formation of the large fault and shear zones, carbon dioxide, water and sulphur reached a high concentration along them. As a consequence the chemical equilibrium was strongly displaced, and chloritization, carbonatization, pyritization, etc. of enormous tonnages of volcanic rock took place. This led to the liberation of silica, potassium, calcium, iron, etc., in addition to gold, silver and other metallic elements present in the rock affected by alteration. These liberated compounds and elements, together with those added to the shear zones by diffusion from the country rocks, migrated laterally and vertically to 'second-degree' low-pressure dilatant zones at shear-zone junctions and other structural locales where contorted zones or openings were formed. In these sites, secondary reactions, promoted by the low-pressure and lower-chemical potential, resulted in the precipitation of quartz, carbonates, auriferous pyrite and arsenopyrite, various other sulphides and sulphosalts and native gold, all of which form the familar gold-quartz-sulphide bodies common in volcanic (greenstone) belts.

In this model the source of the gold is assumed to be the pile composed of various volcanic rocks, intrusive (?) pyritic porphyries and interbedded sediments, especially the iron-formations and sulphide schists, some of which are relatively enriched in gold (Tables 15 and 16). A more local source for the gold (and quartz), however, seems probable in some Precambrian greenstone belts.

Many greenstone belts are marked by great zones of shearing and schisting running for many miles in which the rocks are intensely altered to chlorite schists, chlorite-talc-carbonate schists and in places to great masses of carbonate (ankerite). Some of the gold deposits in greenstone belts are located within the confines of these great carbonated and chloritized zones. Examples are the orebodies of the Giant and Con mines in the Giant-Campbell System, Yellowknife, Northwest Territories and the orebodies of the Kerr Addison and Chesterville mines at Larder Lake, Ontario. Other deposits are in fractures, faults and shear zones that are subsidiaries of the great carbonated zones. Examples are widespread throughout the world, being present at Yellowknife Northwest Territories (Negus-Rycon System subsidiary to the Giant-Campbell System); at Kirkland Lake, Ontario (Kirkland Lake fault subsidiary to the Kirkland Lake–Larder Lake Break); at Ramore, Ontario (Ross Mine where the orebodies are adjacent to extensive carbonated zones); at Porcupine (Timmins) Ontario where belts and patches of carbonatization are widespread both in the productive vein zones and well outside these zones; at the McWatters and other mines in the Rouyn area of Quebec which are in or adjacent to the carbonate-chlorite-talc schist zone that marks the Cadillac Lake Fault; in the Kalgoorlie gold belt of Australia (Golden Mile zone); in Rhodesia; South Africa; and elsewhere.

When rocks are extensively chloritized and/or carbonatized, such as happens when water and carbon dioxide are introduced along great shear systems, there is a major loss of silica as shown by the analyses in Tables 48 and 73. This silica is transferred to dilatant sites in the great shear (schist) zone and fault systems or to similar sites in subsidiary shear zones and faults where it is precipitated mainly as quartz. It is also

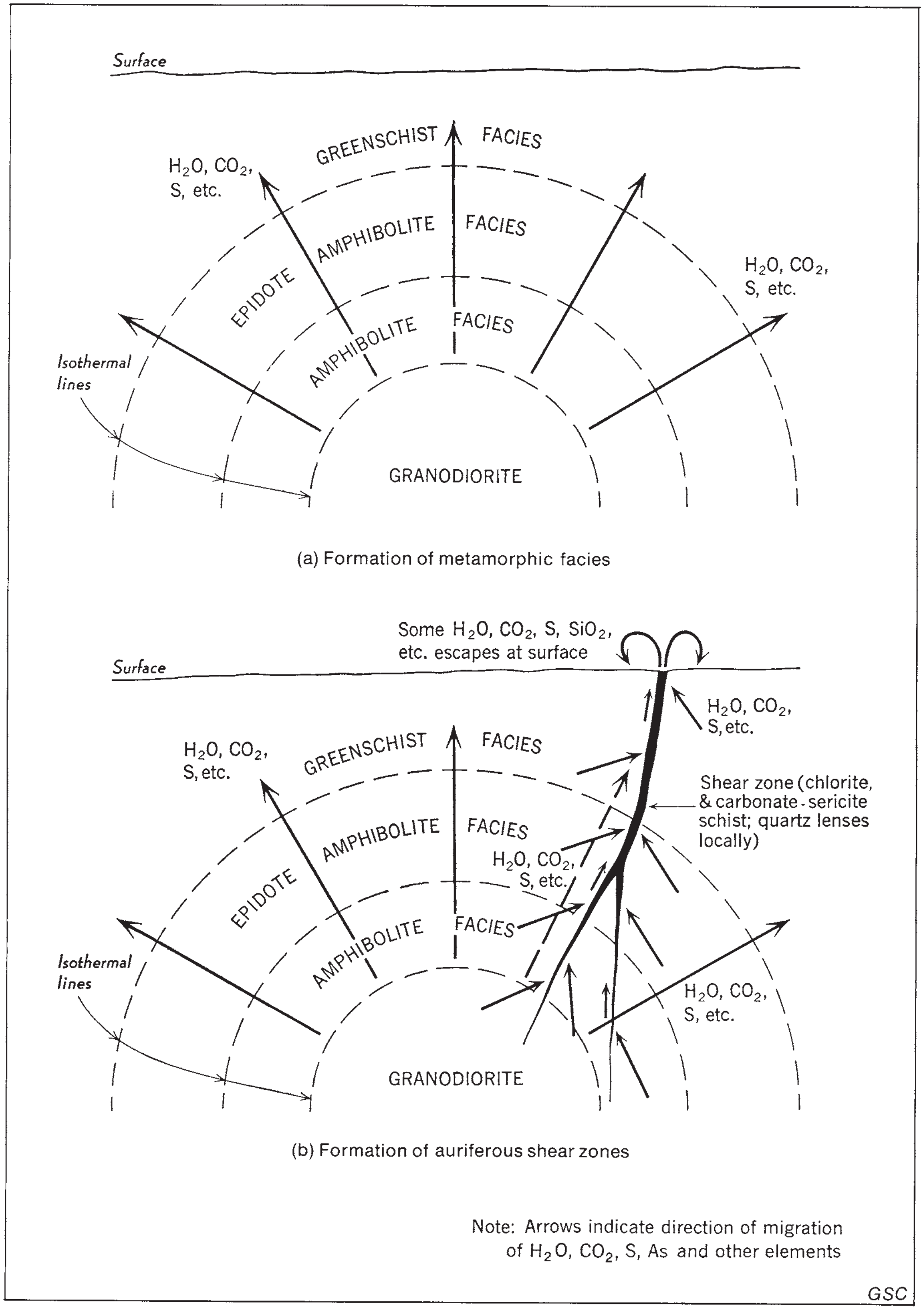


Figure 91. Schematic diagrams illustrating the formation of metamorphic facies and auriferous shear zones.

Table 73. Gain or loss of some constituents during extensive carbonatization of a cubic mile and cubic kilometre of Archean greenstone belts and ultrabasic rocks

Constituent	CO_2	SiO_2	S	As	Sb	Cu	Pb	Zn	Ni	Co	Cr	Au	Ag
		(%)						(ppm)					
Content in volcanic (greenstone) belts prior to carbonatization	0.26	53	0.094	7.0	1.0	80	6	93	123	50	240	0.007	0.12
Content in carbonated greenstone rocks*	8.00	15	0.040	2.0	0.5	25	2	50	80	30	210	0.003	0.05
Gain (+) or loss (–) in short tons (or troy ounces) X10^6 during carbonatization of a cubic mile of greenstone rocks†	+1066.9 (+232.2)	–2067.64 (–450.0)	–7.444 (–1.620)	–0.0689 (–0.0150)	–0.0069 (–0.0015)	–0.758 (–0.1650)	–0.0551 (–0.0120)	–0.593 (–0.1290)	–0.593 (–0.1290)	–0.276 (–0.0600)	–0.414 (–0.0900)	–1.608 (oz) (–12.0g)	–28.14 (oz) (–210.0g)
Content in ultrabasic rocks prior to carbonatization	0.67	40.1	0.047	4.0	0.4	80	4	97	1285	135	2000	0.005	0.08
Content in carbonated ultrabasic rocks*	8.00	30	0.040	2.0	0.2	30	2	50	200	35	1000	0.002	0.05
Gains (+) or loss (–) in short tons (or troy ounces) X10^6 during carbonatization of a cubic mile of ultrabasic rocks‡	+1010.4 (+219.9)	–1392.2 (–303.0)	–0.9649 (–0.210)	–0.0276 (–0.006)	–0.0028 (–0.0006)	–0.6892 (–0.150)	–0.0276 (–0.006)	–0.6479 (–0.141)	–14.956 (–3.255)	–1.3784 (–0.300)	–13.784 (–3.00)	–1.206 (oz) (–9.00g)	–12.06 (oz) (–90.0g)

*These contents are rough estimates from selected carbonated zones. With increase in carbonatization most of the metals decrease significantly to low values, usually only a few parts per million.

†Numbers in parentheses refer to metric tons (or grams) X10^6 gained or lost during carbonatization of a cubic kilometre of greenstone rocks.

‡Numbers in parentheses refer to metric tons (or grams) X10^6 gained or lost during carbonatization of a cubic kilometre of ultrabasic rocks.

probable that much of the gold contained in the mafic silicates, pyrite, oxides (magnetite, etc.) and other minerals in the zones affected by chloritization and carbonatization is liberated and migrates together with the silica into available dilatant zones. It is difficult to prove this contention, although careful work at Yellowknife (Boyle, 1961*a*, p.167) suggests that probably much of the gold in the economic shoots came from the great shear (schist) zones as a result of chloritization and carbonatization. Numerous other elements are also liberated (Table 73), and these probably contribute substantially to the mineral composition of the gold deposits. In recent years the results of investigations by others support the idea that much of the gold in quartz veins and other auriferous deposits may have been locally derived as a result of various alteration processes.

Roslyakova *et al.* (1970) in their investigation of the behaviour of gold in the primary halos of some gold veins (Berikul' and Darasun deposits) noticed that highly altered zones of carbonatization and sericitization constituted negative gold halos, that is the gold in these zones appeared to have been extracted and probably contributed to that present in the veins. They refer to other cases of this phenomenon in the auriferous deposits of U.S.S.R.

Laipanov and Sher (1971) in their study of the wall-rock alteration effects near gold-bearing quartz veins of the Byoryozovsky deposit observed that the carbonatization and chloritization of amphibolites and serpentinites reduced the gold content from 0.015 to 0.008 and 0.004 ppm respectively. They concluded that the gold thus removed was transferred to the veins.

Keays and Kirkland (1972) examined the mobilization of gold at the Thomson River Copper Mine, Victoria, Australia. There, a hornblendite dyke has been extensively sheared, faulted, altered and carbonatized. Cu, Pd, Ir, Au, and to a lesser extent Co and Ni in the main portion of the dyke were shown to have migrated from the sheared and altered rocks and to have been deposited in quartz stringers in a previously segregated body of magmatic sulphides trapped along the footwall of the dyke. Of the various metals noted above, the greatest redistribution was shown by gold.

It should be emphasized in concluding this part of the discussion that not all chloritized and carbonated shear zones are depleted in gold. On the contrary many are slightly enriched in the element as noted in a previous section in this chapter. Many situations actually exist. The most common are shear zones that are slightly depleted in gold throughout much of this extent; other shear and schist zones, however, are depleted in gold in certain parts, either along strike or on their dip, and enriched in others. The latter is the case at Yellowknife where the writer (Boyle, 1961*a*) has shown that silica, and probably also gold, are extracted at depth and have migrated to higher levels where they now form the economic ore shoots. One must think and work in three dimensions on problems of ore genesis.

Considering now the Precambrian sedimentary terranes we see from Tables 15 and 71 that pyritic graphitic shales, argillites, and certain types of sandstones (quartzites) and greywackes are relatively rich in gold (and silver). These rocks were probably the main source of gold in the epigenetic deposits in the Precambrian metasediments. During metamorphism and granitization of the sedimentary piles, silica, gold, silver, sulphur and various base metals were mobilized and drawn into available dilatant zones in drag-folded parts of the beds, along opened bedding planes, along faults, along sheared axes of anticlines and synclines, and along the crests of anticlines (saddle reefs). In all these sites the various mobile constitutents were precipitated as quartz, carbonates, sulphides and native gold. The model suggested for the formation of gold deposits in the sedimentary terranes is essentially the same as that for volcanic (greenstone) belts. In both cases migration of the elements now present in the gold deposits was keyed to the advancing wave of metamorphism and granitization, and the precipitation of the elements depended essentially on structural events. The latter made available dilatant zones in which the elements were precipitated in various mineral forms mainly as a result of differential chemical potentials, the dilatant zones being sites of low pressure and low chemical concentration for specific elements compared with conditions in the stressed and heated host rocks. Where carbonate members occur in the volcanic and sedimentary piles dilatancy was only partly responsible for the precipitation of skarn-type orebodies in most places. More important were the complex chemical reactions between the carbonate minerals and the elements and compounds in the diffusion currents associated with the vanguard of the advancing wave of metamorphism and granitization. In other words the carbonate rocks were chemical traps (chemical potential sinks) that immobilized constituents such as silica, sulphur, base metals, silver and gold, thus precipitating various Ca-Mg-silicates, pyrite, pyrrhotite, arsenopyrite, base metal sulphides and native gold – minerals stable under the P-T conditions prevailing during the formation of skarns.

In some Precambrian (and younger) sedimentary terranes (and in certain mixed greenstone and sedimentary terranes) the precise relationships of the auriferous deposits to metamorphic events, granitization and granitic bodies invading the sedimentary (and/or volcanic) terranes are complex. In many regions the metamorphic, granitic and mineralization events are coeval or nearly so as outlined in the previous paragraph; in other regions, however, some of the quartz deposits appear to be truncated by the granitic bodies, and xenoliths of the quartz veins occur in the granitic rocks. In a few places (e.g., Yellowknife) some of the auriferous quartz veins are cut by pegmatites. Such relationships are common where there are two ages of granitic rocks in the terrane as in the Precambrian Yellowknife Supergroup and in the Ordovician Meguma Group of Nova Scotia. Generally the first phase is a biotite granite, whereas the second is a muscovite granite usually with a plethora of associated pegmatites. Where these geological features exist the sequence of events seems to have been:

1. Initial stage of folding of greywacke and slate (and volcanics) with the concomitant effects noted in 2 below.

2. Rise of the geotherms through the sedimentary (and/or volcanic) pile due to metamorphism and granitization at depth. This is attended by the migration of silica, sulphur, arsenic, gold and other constituents into available dilatant zones to form the saddle reefs, leg reefs, interbedded veins, stockworks, lodes and other auriferous bodies with their contained auriferous sulphides and native gold.

3. Continued folding resulting in the corrugation of the quartz veins, formation of quartz boudins, ptygmatic veins and a general crushing and recrystallization of the quartz. During this period remobilization and reconcentration of the initial gold into dilatant sites (shoots), commonly as the native metal, may take place in the quartz bodies. In addition further increments of gold, sulphur, arsenic, silica and other constituents may be provided by the prevailing diffusion currents.

4. Continued granitization at depth followed by the injection of high level granitic stocks and small batholiths. The development of pegmatites commonly takes place during this stage.

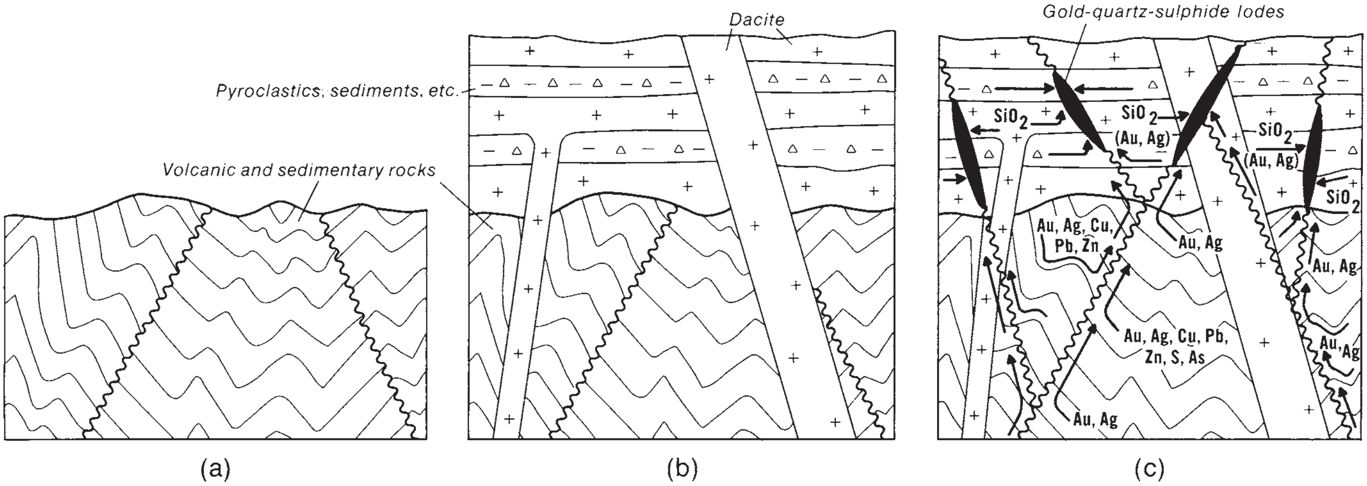
5. Late stage minor folding and faulting.

The epigenetic gold deposits formed during Paleozoic, Mesozoic and Cenozoic times are essentially similar in most repects to those of Precambrian age.

There are some differences, but these are minor. For instance, great zones of shearing, schisting, chloritization and carbonatization are not common in rocks younger than Mesozoic, but their place is taken by enormous irregular zones of pervasive propylitization. It is from these zones that some of the silica, sulphur, base metals and gold in the veins may have come, having been liberated from the andesites, pyroclastics, etc. during hydration and carbonatization processes (Fig. 92).

Another model is possible for the origin of certain gold deposits in rocks lying in older geological terranes (e.g., Paleozoic rocks on Precambrian terranes; Tertiary andesites and pyroclastics lying on Mesozoic rocks). In this model (Fig. 92) the source rocks for much of the gold and its associated elements may be underlying pyritic graphitic schists, volcanics, etc., and the receptacle rocks for the deposits may be overlying faulted and fractured andesites, pyroclastics, limestone, etc. During igneous activity the heat wave associated with intrusive bodies or granitization fronts liberates water, carbon dioxide and other volatiles from the basement rocks, and these in turn promote the migration of silica, sulphur, base metals, silver and gold. These rise into the available dilatant zones such as faults, fractures and breccia pipes where they are precipitated as quartz, sulphides and native gold. Such an ore genesis model as this appears to answer many of the problems associated with the formation of Tertiary epigenetic gold deposits. In this respect it is of interest to note that many of the basement rocks underlying Tertiary deposits in many parts of the world are Mesozoic or older graphitic, pyritic schists, greywackes and slates and volcanic assemblages, rocks that are commonly enriched in gold, silver, sulphur and the various base metals now present in the Tertiary gold deposits.

Our present knowledge of the migration of gold and its associated elements during metamorphic events, or as a result of extensive alteration effects such as chloritization and carbonatization, is meagre, and this is one of the weak points in all metamorphic secretion theories. In a previous section diffusion in its many manifestations has been considered as the most probable process by which gold is transferred from source rocks to the deposits. At Yellowknife it cannot be shown conclusively that the gold and its accompanying elements came from the country rocks, although there is a strong suggestion that much gold was liberated within the shear zone systems during carbonatization and chloritization



(a) Metamorphosed, folded and faulted volcanic-sedimentary basement complex

(b) Basement complex is overlain by andesites, pyroclastics and sediments, and the whole is intruded by dacite porphyries, etc. This is accompanied by a rise in the geotherms through the basement complex

(c) Late faulting and fracturing coeval with or followed by propylitization of the volcanic pile; mobilization and migration of SiO_2 from zones of propylitization; contemporaneous mobilization, migration and concentration of gold, silver, base metals, etc. into lodes, the source of these elements being the rocks of the basement complex as well as the zones of propylitization in places

Figure 92. Schematic diagrams illustrating the sequence of events in the formation of certain gold-silver epithermal deposits.

and migrated into local dilatant zones. The chemical profiles for water, carbon dioxide and sulphur across the metamorphic zones of the greenstone belt are, likewise, highly indicative of a process whereby these constituents were driven out of the high temperature zones (amphibolite facies) into the low temperature zones (greenschist and chloritized shear zones) (Boyle, 1959; 1961*a*, p. 85). Confirmatory evidence is provided by sulphur isotope studies done on samples from traverses across the metamorphic facies in the greenstone belt (Wanless *et al.* 1960).

Others have observed a variety of phenomena that suggest gold is relatively mobile during the metamorphism of rocks. Some of these involve the injection of dykes into auriferous deposits. At Yellowknife and in the Little Long Lac–Sturgeon River gold belt of Ontario, particularly the latter, gold is extensively mobilized near basic dykes that cut across the orebodies. For example, at the Northern Empire Mine east of Beardmore (Fig. 46), a flat diabase sheet cutting across the gold ore shoots is accompanied by an alteration halo some 50 ft or more thick in which gold and much quartz has been leached and dissipated (Benedict and Titcomb, 1948). Similar phenomena occur in other parts of the world and are notable near dykes cutting the bankets of the Rand in places (Sharpe, 1955; De Kock, 1964). While these examples are microphenomena compared to regional metamorphic events they do, however, show that gold is relatively easily mobilized where a thermal gradient prevails.

The behaviour of a variety of elements during the metamorphism of various types of rocks has been studied in the Patom Highland of U.S.S.R. by Petrov and Makrighina (1971) and Petrov *et al.* (1972). In the first paper the authors found a number of petrogenic and rare elements such as Li, Rb, Ba, Sr, etc. to behave inertly whereas Fe, Co, Ni and Au showed considerable migration. Aided by volatiles these elements moved down the temperature gradient and accumulated in the lower temperature facies (epidote-amphibolite and greenschist). In the second paper the Au, U, Th and K contents were determined in meta-pelites, calcareous mudstones, marls, limestones and sandstone. During metamorphism gold was found to exhibit significant changes in content in meta-pelites and siltstones, i.e., in rocks that were initially rich in water. Furthermore, the meta-pelites lost gold from the amphibolite facies with a consequent gain in the epidote-amphibolite and greenschist facies. U, Th and K were found to be largely immobile during metamorphism.

These tendencies, however, do not appear to be unequivocal. Li (1974*a,b*) and Li and Shokhina (1974*a,b*) for example noted no significant change in the gold content during progressive metamorphism of Precambrian rocks on the Yenisei Ridge, Siberia, U.S.S.R. Even under very high temperature conditions (granulite facies) the only result was a local redistribution and dispersal of gold.

Petrov (1974), in an exhaustive study of the genesis of the gold-quartz veins of the Yenisei region, concluded that the gold mineralization resulted from three primary factors: (1) the gold content of the sedimentary-metamorphic rocks; (2) the development of fissure zones in these rocks, which was connected with folding and dragging associated with extensive faulting; and (3) the development of 'chemical differentiation' of the rock in the zones of fracturing and fissuring. By 'chemical differentiation' Petrov indicated that the gold and other elements can quite easily be derived from the host rocks. He defined 'chemical differentiation' as a typically ore-producing 'hydrothermal' process, similar to metamorphic differentiation in the kinetics of chemical reactions and the transfer of matter, but separated from metamorphic differentiation in time. 'Ore-producing' chemical differentiation manifests itself before or after metamorphism and metamorphic differentiation, and it is also possible for it to appear in the initial and final stages of these processes but not together with them. When considering the genesis of quartz veins alone and particularly in the North Yenisei region, Petrov (1974) clarified the definition of 'chemical differentiation' as follows:

> During the formation of quartz veins, chemical differentiation is that process of the diffusional rearrangement of rock matter as a result of which there occurs a concentration of silica in some volume of that rock and the complete concentration of some ore components earlier disseminated in that volume more or less uniformly in the forms of veins, veinlike masses and deposits of composite form. 'Ore-producing' chemical differentiation is not directly linked with magmatic activity; its closeness to metamorphic differentiation is due solely to their common relationship to tectonic stresses, which serve as a kind of trigger for both processes.

In another part of this most interesting work Petrov (1974) carried out experiments on the geological diffusion of silicon under stress (tectonic) conditions. When tension fissures formed under compression were available the rate of diffusion of silicon was of the order of 1 to 3 × 10^{-5} cm^2/s, which is 10^5 times more than the diffusion coefficient of silicon commonly quoted in the literature. These values agree reasonably well with those calculated and observed for silver by the writer many years ago, (Boyle, 1968*b*). As Petrov (1974) indicates these rates mean "that quartz veins with a thickness of about one millimetre may arise in nature in less than a year."

Detailed mechanisms of the formation of epigenetic gold deposits

General characteristics of epigenetic gold deposits. In the previous section the generalized mechanisms of the formation of epigenetic gold deposits were outlined. This section will deal with the details of the mechanisms, specifically with parameters such as localizing structures and chemically favourable host rocks, dilatancy, migration and redistribution of the ore and gangue elements, and the temperature and pressure conditions under which the deposits are thought to have formed.

Following the views of the structural geologists, one recognizes two extreme zones in the crust of the earth where auriferous veins, lenses and other types of deposits may form – the near surface zone of fracture and the deep zone of flowage and metamorphism where open fractures and cavities are largely inhibited. An intermediate zone combines the features of both these zones to a degree dependent upon the prevailing tectonic and geochemical conditions. These conceptions are fundamental, and they influence greatly the types of gold deposits that will form.

No particular figures can be ascribed to the lower limit of the low load zone of fracture in tectonic environments, since many factors are involved depending upon the types of rocks and the nature of the applied forces. For normal rock piles (volcanics and sediments) the lower limit of the fracture zone is probably at 4000 m. Below this the intermediate zone continues to 8000 m or slightly more, below which the great load would inhibit the general presence of cavities and open fractures for any length of time.

In the zone of fracture, especially under near-surface conditions, open structures such as fractures, faults, breccia zones and porous zones are formed and preserved, and these become filled with groundwater, connate water, metamorphic water[29], or mixtures of these. Under certain conditions this water will form a static medium through which ore and gangue constituents derived from the country rocks will migrate in the form of ions, hydrated ions, molecules and gases to sites of deposition determined by differences in the chemical potential of constituents in the system. Under other conditions the water may be in motion, and mass transport and subsequent deposition of dissolved constituents gathered from the country rocks will take place. Even under these conditions diffusion processes are at work, but they are of a short-range nature, whereas in the first situation they are of a relatively long-range order. In rare cases the movement of constituents in the fractures, faults, etc. may be entirely in the gaseous state.

In the zone of flowage and high grade metamorphism the exact state of water cannot be accurately defined. Below the critical temperature (273°C) it probably exists as a gas, above this point as a dense gas. In both cases it would pervade all grain boundaries and other discontinuities in the rocks thus forming a more or less stationary medium through which diffusion of gold, silver, base metals and gangue constituents may take place. In other circumstances, as in rocks undergoing very high grade metamorphic changes, water may be largely expelled from the rocks, thus necessitating a dry diffusion of constituents along grain boundaries and other discontinuities.

Gold deposits formed in the zone of fracture are usually of two types: veins and lodes generally of the gold-quartz type deposited in faults and fractures; and disseminated deposits developed near faults and fractures in chemically reactive or porous and permeable rocks, usually limestones, dolomites, argillaceous/arenaceous carbonate rocks or a variety of carbonate-bearing sandstones, arkose, etc. The structures, textures, and paragenesis of the mineral aggregates of these two types of deposits are characteristic.

In the veins and lodes deposited in the zone of fracture open cavities and vugs are abundant and open space filling manifested by crustified growth banding, comb structures, cockade structures, delicate colloform banding and intricate lamellar quartz aggregates are characteristic (Pls. 4, 12 and 13). Quartz with massive structure is common in some deposits, but book and ribbon structures in quartz are relatively rare. Early precipitated minerals such as calcite and barite are often replaced, sometimes pseudomorphously, by quartz and/or adularia. Such phenomena suggest major changes with time in the composition of the mineralizing media or in the conditions of deposition. Replacement of fault breccia and gouge, represented by silicification, sericitization, carbonatization, pyritization, alunitization, etc. is common, but the vein matter is generally frozen to the walls. Wall-rock alteration zones are characteristically developed in some rocks, subdued or practically absent in others. (*See also* the section on wall-rock alteration in this chapter.) In cafemic rocks (andesites, chlorite schists, etc.) the zone developed adjacent to the veins and lodes is characterized essentially by carbonatization, sericitization and pyritization. This grades outward through a chloritized-carbonatized zone into a weakly chloritized zone and ultimately into fresh rock. In acidic

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[29] Metamorphic water is here defined as that water expelled from deep zones as a result of the dehydration of shales and other hydrous rocks undergoing regional or thermal metamorphism.

rocks (granite, rhyolite, gneiss, etc.) the alteration zones are generally less distinct but commonly include a sericitized and pyritized zone adjacent to the veins and lodes and an outer sericitized or argillized zone, which grades imperceptibly into the fresh rock. Silicification may occur in places, commonly in the zone nearest the veins or lodes. Argillization is widespread in all zones in some deposits as is also alunitization. Most alteration zones are marked by an increase in the K_2O/Na_2O ratio as the veins are approached. Propylitization, alunitization and silicification, particularly the first two, may assume a regional aspect in some areas. Loss of silica is marked where hydration, carbonatization, propylitization and alunitization processes are manifest. The silica is evidently delivered to the fissures and faults where it crystallizes as quartz.

The distribution of the gold in the vein deposits formed in the zone of fracture is characteristic. Most of the precious metal occurs within the vein filling or in seams along the contact between the vein filling and the wall rocks. The characteristic wall-rock alteration zones generally contain only minor amounts of gold, and the gold values drop off rapidly with distance from the vein. Only rarely can the vein filling and wall-rock alteration zones be profitably mined as a whole.

The disseminated deposits in the zone of fracture are rudely tabular, commonly stratiform, occasionally pipelike and usually have a compact to moderately porous, fine-grained to coarse texture, the gold and auriferous minerals being disseminated, or occasionally arranged in rude bands throughout a groundmass of various minerals, some residual and some resulting from alteration and mineralization processes. In the lower temperature deposits, developed mainly in carbonate rocks, argillaceous/siliceous carbonate rocks or carbonate-bearing sandstone, quartzite, etc., the alteration effects are mainly silicification, sericitization, argillization, chloritization, alunitization and pyritization, together with the introduction of a variety of elements, mainly Au, Ag, S, As, Sb, Ba, Zn, Cu, Pb, Hg, W, Mo, Se and B. There is generally a major abstraction of CO_2 (carbonate) and an introduction of K, the latter usually resulting in an increase in the K_2O/Na_2O ratio in the ore zones compared with the unaltered host rocks. The higher temperature disseminated deposits are developed in similar host rocks, and the elemental introductions and abstractions are essentially similar. The resulting groundmass minerals are, however, different. Instead of silicification and argillization the deposits are marked essentially by the development of a compact skarn or hornfels manifest by the presence of a variety of Ca-Mg-Fe-silicates such as garnet, epidote, etc. Skarn-type gold deposits formed under near surface conditions are, however, relatively rare.

In both the vein and lode deposits formed in the zone of fracture successive bands or crusts of ore minerals commonly permit a general paragenesis to be determined, but numerous studies by many investigators show that the succession is commonly complicated, contemporaneous deposition of minerals, incomplete sequences, minor reversals, omissions and partial repeated sequences punctuated by fracturing being frequently encountered. In the compact disseminated deposits a paragenetic sequence of the ore and gangue minerals can generally be made out by microscopic methods. Disregarding details and various complications the common paragenetic sequence in both types of deposits is (1) quartz, carbonates, sericite, feldspars, pyrite, pyrrhotite and/or arsenopyrite followed by (2) sphalerite, (3) chalcopyrite, tetrahedrite, tennantite, enargite, (4) galena, (5) acanthite, (6) stibnite and various Fe, Cu, Zn, Pb, Ag antimony sulphosalts, and (7) gold and gold tellurides. A more detailed paragenesis is given later.

The position of gold in the paragenetic sequence is of interest. In some deposits the early pyrite and/or arsenopyrite are often auriferous, the metal being present in lattice sites or as finely divided submicroscopic particles in the sulphides. In nearly all deposits the gold and gold tellurides are the last minerals to crystallize. In massive quartz veins, and even in some of those that exhibit comb structures and depositional banding, the quartz and early pyrite and/or arsenopyrite are crushed, fractured, sheared or brecciated, the gold and tellurides being deposited often with clear limpid quartz and carbonates in the fractures, crushed zones, shears and interstices between the breccia fragments. In the literature mention of this feature is repeated *ad infinitum* and is discussed at length by Bain (1930) and White (1943), and figured in many beautiful specimens by Ebbutt (1948).

Deposits formed deep within the earth in the zone of flowage have many features in common with those formed in the zone of fracture, but there are major differences as well.

The deposits are of two types: veins, lenses, saddles and irregular bodies in shear zones, schist zones and fractures; and replacement bodies in chemically favourable rocks. The structures and textures of the mineral aggregates in these two types of deposits are characteristic.

In the veins, lenses, saddles, etc., the quartz, which generally makes up more than 90 per cent of the bodies, commonly has a compact texture and is medium to coarse grained but locally highly mylonitized with innumerable recrystallized sections and phantom veinlets. There may be a rude banding in the quartz, but depositional banding of quartz and other minerals and comb structures, cockade arrangements and vugs are relatively rare. A characteristic feature is the presence of book structure (parallel quartz sheets sandwiched between slabs of wall rock) and ribbon quartz (Pl. 3), the origins of which have been long discussed and variously interpreted (McKinstry and Ohle, 1949; Chace, 1949; Stillwell, 1950, 1953*b*). The chief hypotheses that have been suggested to explain book structure are: accretion of quartz along parallel lines of weakness, replacement processes along similar lines, inflation of lines of weakness by invading solutions and the force of growing crystals. For the origin of ribbon quartz the alternative hypotheses are the same with the addition of post-quartz shearing processes. Probably all of these mechanisms have operated in the formation of deep-seated quartz veins, lenses and saddle reefs; the argument is really over which is the most important mechanism. To the writer the activating agency that results in the formation of book and ribbon structure is dilation, both macro and micro, attendant upon shearing, faulting and the opening of the crests of folds promoted mainly by obliquely directed compressive forces. According to this concept quartz lenses are the result of repeated formation of incipient openings in shear zones, faults and saddles, where sheeting, buckling, dragging and mashing of the wall rock was prevalent. These openings and contorted zones are sites of low pressure and low chemical potential into which mineral matter (mainly silica) migrated and was deposited. Large composite quartz lenses and veins marked by ribbon quartz evidently grew mainly by accretion of numerous small quartz lenses filling dilation zones. Once these small lenses were formed, repeated warping and dragging resulted in recrystallization of the quartz and further dilation, drawing in more silica. This action, together with some replacement, tended to obliterate the seams and patches of wall rock, mainly schist, surrounding the small lenses, and the final result was ribboned quartz lenses or bodies of massive quartz containing trains of sericite, chlorite, carbonate, etc., which mark the sites of former ribbons.

The deep-seated auriferous skarn-type deposits are generally irregular bodies or bunches of ore but some are tabular and stratiform. Their texture is compact and coarse, characteristics of replacement processes under high temperatures and pressures. Banding, crustification and vugs may occur, but they are infrequent and local. The characteristic minerals, mainly Ca-Mg-Fe silicates and the various oxides and sulphides, are essentially similar to those formed in skarn deposits developed near the surface.

The wall-rock alteration effects in deep-seated auriferous veins, lodes and skarn-type deposits are similar to those mentioned for the near surface deposits. The alteration effects are, however, commonly more marked in the deeper deposits. Alunitization and argillization are rare in the deep deposits whereas tourmalinization, biotitization and ankeritization are particularly common. Epidotization is, likewise, common in some deep-seated deposits, and minerals like garnet, andalusite and amphiboles make their appearance in some of the alteration sequences. Gold (and silver) is commonly present in the alteration zones of these deposits and may contribute substantially to the worth of the ore, the ore boundaries being determined in many cases by assay. Occurrences are even known where the bulk of the gold is in the altered rock whereas the vein materials are relatively barren.

The paragenetic sequence of the minerals in the deep-seated deposits is essentially similar to that described above for the deposits formed in the zone of fracture under near surface conditions.

It is well known that gold is rarely if ever distributed uniformly throughout its deposits; more generally the element is concentrated in specific zones referred to as ore shoots. Mention of these has been made at various places in the preceding text, and it now remains to summarize the features of these phenomena and suggest reasons for their occurrence.

Ore shoots can be defined as zones with definite boundaries within deposits that can be mined at a profit under normal conditions of mining. As such they depend, therefore, essentially on the content of useful elements they contain; in the case of most auriferous deposits this generally means the content of gold, although in certain deposits closely associated elements such as Cu, Ag, Pb, Zn, Bi, Te, etc. may be won as a byproduct. The delineation or blocking out of ore shoots is usually done by sampling and assaying, which in the case of auriferous deposits requires considerable experience and care because of the camouflaged occurrence of the element (e.g., gold in pyrite or arsenopyrite) and the particulate and dispersed nature of native gold. Novices evaluating gold deposits and organizing sampling programs for the delineation of ore shoots should consult textbooks on the subject such as those by Forrester (1946) and McKinstry (1948) before commencing work.

Ore shoots are regular to highly irregular in outline; commonly elongate and pipelike or chimneylike in form and large or small in tonnage. Their geometry is defined by their width or thickness, their breadth, their stope length and their pitch length. Deposits may contain only one ore shoot, although most contain several separated by barren (uneconomic) mineralized material. In origin ore shoots may be of primary (hypogene) or supergene derivation. The general nature and causes of ore shoots are discussed at considerable length in Lindgren (1933), Newhouse (1942) and Bateman (1950). In the following text, discussion is restricted to hypogene ore shoots in auriferous epigenetic deposits such as veins, stockworks and replacement deposits. Localization of ore shoots in the quartz-pebble conglomerate type of deposit is discussed in the previous section, and an outline of the causes of auriferous supergene ore shoots is given in Chapter IV.

The distribution of ore shoots in auriferous deposits is not fortuitous, although in some cases their causes may be elusive and due to factors that are not readily determined. The localization of ore shoots in auriferous deposits may be due to tectonic (structural) features, physico-chemical (pressure, temperature, concentration) factors, or a combination of both. As discussed subsequently tectonism produces a variety of dilatant features that control the migration and deposition of gold and its accompanying elements in deposits and more specifically in ore shoots. Various physico-chemical factors such as the type of wall rock and its porosity, the mingling of solutions and diffusion currents, and changes in temperature and pressure as solutions, gases and diffusion currents rise toward the surface also exert an influence on the deposition of gold in ore shoots.

The causes of localization of auriferous ore shoots in deposits can usually be ascertained by careful geological, mineralogical, chemical and assay work, paying particular attention to types of primary and secondary structures, types of wall rocks and the type and degree of wall-rock alteration. When the various geological and mineralogical features and the assay and chemical data are plotted and the latter contoured on plans and sections, particularly longitudinal sections, of the deposits certain relationships generally emerge between the location of enrichments of gold (ore shoots) and features such as the curvature of faults or shear zones, impermeable barriers and favourable wall rocks. Once an ore shoot control is established the search for other shoots is commonly facilitated.

Ore shoots controlled by secondary or superimposed structural conditions. Structural distortion of rocks related to shearing, faulting, fracturing, brecciation and folding produces various types of dilatant features that are sites of low chemical potential where gold and its associated elements concentrate according to physico-chemical principles discussed subsequently. Some of these dilatant features include:

1. Open zones and discontinuous cavities caused by strike slip or dip slip movements of opposite walls along a curved or irregular fissure, fault or shear zone: Ore shoots localized in such zones are generally lenselike in form and commonly have

extensive pitch dimensions. Many of the auriferous ore shoots in the Yellowknife Greenstone Belt owe their origin to their type of dilatancy (Boyle, 1961*a*), and a number of the ore shoots in the Mother Lode System of California are considered by Knopf (1929) to have had such an origin.

2. Open spaces, brecciated zones, and contorted, dragged, mashed and shattered zones at the intersections or junctions of fissures, faults or shear zones: In addition to dilatancy such sites may also produce a large surface area of comminuted rock for chemical interaction with solutions or diffusion currents. Ore shoots localized in such sites may be pipelike, saddlelike, lenselike or irregular in form. Most have limited strike dimensions but extensive pitch dimensions. Many of the auriferous ore shoots in the Yellowknife Greenstone Belt are at shear zone junctions (Fig. 18). Most of the ore shoots in the Grass Valley veins in California are at vein intersections.

3. Dragged, crenulated, severely contorted and dilated sites in wide schist or shear zones: Such zones in addition to producing dilatancy along myriad contorted sheetlike openings also provide a large surface area of comminuted rock for chemical reaction with migrating solutions or diffusion currents. Many of the auriferous ore shoots in greenstone belts at Yellowknife, Timmins, Kirkland Lake (Kerr Addison) and western Quebec are localized in such sites.

4. Tension fractures in wide schist and shear zones: Where these are closely spaced they become filled with gold-quartz veins and stringers that constitute irregular stockworks or en echelon ore shoots. Some of the orebodies in the Con Mine at Yellowknife and the Kerr Addison and Chesterville mines at Larder Lake (Fig. 23) are of this nature.

5. Dilatant zones created by slippage, shearing or faulting along the walls of quartz veins and lenses: These zones originate as the result of late movements and commonly contain significant enrichments of gold in many auriferous belts.

6. Open spaces along faults, shears and fractures and brecciated, dragged and contorted zones in competent rocks below or otherwise associated with impervious barriers such as shale, slate, igneous rocks, fault gouge: These barriers being athwart the dilatant zones, pond solutions and otherwise obstruct diffusion currents, giving rise to impounded ore shoots. Some of the auriferous lodes at Keno Hill, Yukon are of this nature (Boyle, 1965*a*).

7. Dilatant zones created by tension fractures, shrinkage joints, or small faults and shears in dykes, sills, competent lava flows and massive sedimentary beds: These give rise to ladder veins (shoots) and en echelon veins and lodes. Examples are numerous in the Beresovsk gold belt of U.S.S.R. and elsewhere (Figs. 19, 52, 53 and 54).

8. Dilatant zones associated with pipes and chimneys: These have various origins including brecciation and comminution of rocks at the intersection of faults, fractures, shears or joint systems; throats of old volcanoes; diatreme breccia pipes or volcanic explosion vents; and solution channels and callapse structures in carbonate-bearing rocks. Ore shoots in these sites generally have short plan dimensions but extensive pitch dimensions. Examples are common in auriferous belts (e.g., Cresson Blowout, Cripple Creek, Colorado, Figs. 35 and 36; Sunbeam Kirkland auriferous pipe in the Falcon Lake stock, Manitoba, Fig. 51).

9. Extensive zones of fracturing, faulting, crushing and brecciation developed in dykes, sills, competent lava flows and massive sedimentary beds, intrusive plugs, stocks and small batholiths: Such dilatant zones commonly encompass very large volumes of rock that constitute the ore shoots. In some cases, however, enriched zones in great volumes of fractured and altered rock embody individual randomly distributed ore shoots. Deposits in this category include the so called 'porphyry gold deposits' by analogy with the 'porphyry copper deposits'. Examples of low grade porphyry gold deposits are widespread. They are described in a previous section. (*See especially* Figs. 49 and 50.)

10. Dilatant zones related to openings on the crests of anticlines and less frequently in the troughs of synclines: During regional folding these zones give rise to the classical saddle reefs (Figs. 38, 39, 40 and 44) so common in terranes of greywackes and quartzites interbedded with slates and phyllites. In saddle reefs the richest ore shoots are predominantly localized in the caps of the reefs and regionally on domes.

11. Dilatant zones in tension fractures, faults and shear zones along the sheared or faulted axes of anticlines and synclines. Shoots in these sites tend to be lenselike in form; most have a short strike dimension but commonly extend to considerable depth.

12. Dilatant zones created during regional folding by drag folding, shearing, brecciation and contortion of incompetent sedimentary beds, tuffs and volcanics. Such zones give rise to leg reefs (shoots) in isoclinally folded strata (Figs. 38, 40 and 41), lenselike and irregular lenselike shoots in tuffs and other rocks (Fig. 55) and irregular ore shoots in rolls, drag folds and other contortions in iron-formations (Figs. 56 and 57).

Ore shoots controlled by chemical conditions. It is axiomatic to state that all ore shoots are precipitated in sites of low chemical potential; in certain cases decreases in pressure and temperature are the promoting agencies for precipitation, whereas in other cases changes in the concentration (stability) factor of elements (or their complexes) in solutions or diffusion currents are paramount in causing widespread precipitation due to interaction with reactive wall rocks, entry into porous zones, and so on. Some of the conditions where this takes place include:

1. Shoots controlled by steep temperature and pressure gradients: As mineral laden solutions or diffusion currents rise from depth they eventually enter zones of lower temperature and pressure where precipitation takes place as a result of the P-T factor in the chemical potential. In some conduits (faults, shears, fracture zones) the P-T gradients are steep and a marked vertical zoning may result as in certain auriferous Tertiary terranes (Hauraki goldfield, New Zealand; Transylvania goldfield, Romania); in other conduits the gradients are so flat that precipitation takes place over a long vertical interval as in certain auriferous deep seated deposits (Kolar, India; Kirkland Lake, Ontario).

2. Ore shoots controlled by intermediate, basic and ultrabasic wall rocks: When mineralizing solutions and diffusion currents laden with H_2O, CO_2, S and As react with ultrabasic, basic and intermediate rocks such as serpentinites, basalts and andesites extensive changes take place resulting in the binding of Fe, Ca, Mg and Mn in the rocks by CO_2, H_2O,

S and As to form carbonates, chlorite, pyrite and arsenopyrite. Silica, which is released, contributes to the vein fillings. The alkali-bearing sulphide, sulphide-arsenide and sulphide-antimonide gold complexes are broken down, the alkalies (K and Na) forming sericite and/or albite and adularia, and the gold precipitating in pyrite, arsenopyrite or as the native metal. These various processes are discussed at length in the sections on natural waters (Chapter II) and wall-rock alteration (Chapter III).

3. Ore shoots controlled by carbonaceous wall rocks: These are the auriferous ore shoots controlled by the so-called 'indicators', which are numerous in certain gold belts but particularly at Ballarat, Victoria and Gympie, Queensland. The action of the so-called indicators is probably due to the marked reduction and precipitation effect that carbonaceous matter has on gold solutions. (*See also* the section on gold in natural waters.)

4. Ore shoots controlled by iron sulphide– and iron oxide–rich rocks: Pyritiferous and pyrrhotiferous iron-formations in many parts of the world have a marked precipitating effect on gold solutions, examples being the Central Patricia and Pickle Crow mines in Ontario (Figs. 20 and 21). The rich auriferous ore shoots in quartz veins adjacent to highly pyritiferous amphibolites at Ophir in California are further examples of the phenomenon. The function of sulphide– and iron oxide–rich rocks in precipitating gold has been established experimentally. (*See* the section on gold in natural waters.)

5. Ore shoots controlled by carbonate-bearing rocks: Carbonate-rich rocks such as limestones, dolomites and calcareous shales notably control the location of auriferous ore shoots under both high and low temperature conditions. The reason for this is evidently the ease with which these rocks can be replaced and the neutralizing effect they have on neutral to slightly acid ore solutions and diffusion currents. Under high temperature conditions skarns with auriferous shoots in pyritic and arsenopyritic zones are formed (e.g., Nickel Plate and French mines at Hedley, British Columbia); at low temperatures siliceous zones with ore shoots enriched in gold, silver, pyrite and a variety of sulphides and sulphosalts result as at Carlin Nevada (Figs. 58 and 59) and Salsigne, France (Fig. 42).

6. Ore shoots controlled by primary (initial) porosity conditions: Such conditions exist initially in porous sandstones, grits and conglomerates; in volcanic breccias, volcanic explosion vents, diatremes, vesicular lava flows and certain tuffaceous rocks; and as a result of solution phenomena during diagenesis that give rise to solution cavities, collapse breccia structures and so on. These porosity conditions are sites of low concentration and have given rise to auriferous ore shoots in many gold belts, examples being Salsigne, France (Fig. 42) where some of the ore shoots occur in initially porous grits and phyllitic quartzites and Cripple Creek, Colorado (Cresson Blowout, Figs. 35 and 36) and Central City district, Colorado (The Patch, Fig. 48) where fabulously rich ore shoots occurred in volcanic breccia pipes.

In concluding this discussion on auriferous ore shoots it should be emphasized that conditions for rich and highly productive shoots (bonanzas) in deposits are most propitious when a conjunction of both structural and chemical factors are present. Another particularly favourable condition prevails when quartz veins and other auriferous deposits have been intensely sheared, brecciated and recrystallized resulting in the remobilization of gold from sulphides in the deposits followed by its concentration mainly as the native metal in well defined shoots marked by tensional dilation cracks, fissures and discontinuities in gangue minerals and along such features as the contacts between veins and their wall rocks. Such conditions are most commonly found in deep seated (Precambrian and Paleozoic) deposits; in shallower deposits such as those in Tertiary terranes similar phenomena may obtain but more generally brecciation and reopening of veins due to recurrent movements results in pulsations of mineralization from sources exotic to the deposits, and these precipitate gold and other minerals in the new fractures, brecciated zones or along the contacts of veins and wall rocks. The subject of the remobilization of gold and multiple generations of gold is discussed below.

Temperature, pressure and pH conditions of gold deposition in epigenetic deposits. Estimates of the temperature-pressure conditions of formation of auriferous epigenetic deposits have been made for many years utilizing mineral intergrowths and thermal stabilities, pyrite geothermometer, sphalerite geothermometer, decrepitation, isotopic data and liquid inclusion data. What follows is a general summary of a few of the multitudinous investigations extant in the literature.

The techniques of studying liquid inclusions in minerals and decrepitation methods are described at length by Scott (1948), Smith and Peach (1949*a,b*) and Peach (1949). There is an extensive review and bibliogrpahy on both subjects by Smith (1953), and the more recent investigations are covered in the works by Kashiwagi *et al.* (1955), Takenouchi (1962), Yermakov *et al.* (1965) and in the Proceedings of COFFI (Roedder, 1968–1974).

A brief summary of the fundamentals of liquid inclusion and decrepitation research in determining temperatures and other features of ore deposition as it pertains to gold follows.

In general, quartz contains two types of liquid inclusions. These have been called primary inclusions and secondary inclusions depending upon their nature and location in the quartz crystals and grains. Primary liquid inclusions occur along growth planes, interlineage boundaries and other crystal discontinuities and are thought to have resulted from the trapping of some of the fluid from which the quartz grew. Secondary liquid inclusions occur along healed fractures, around grain boundaries and in small, clear crosscutting (phantom) veinlets. In most thin sections of vein quartz, trains of secondary inclusions cut across grain boundaries and hence appear to have formed by the trapping of some liquid from solutions migrating along grain boundaries and fractures that formed after the deposition of the quartz crystals and grains. Inclusions in the minerals of gold deposits may be simple or complex. Some contain only gas at room temperature; others contain at least one liquid phase at room temperature, generally water plus a gas bubble. Salt crystals of various types are common in some inclusions, and hydrocarbons (petroleum) have been noticed in a few inclusions from certain, usually young, deposits. Studies of the salt content of primary inclusions are useful in understanding the chemistry of ore-bearing solutions, provided that certain assumptions are valid.

In the ideal case at the temperature and pressure of formation of both primary and secondary liquid inclusions the trapped liquid would just fill the inclusions. During the drop in temperature and pressure to that prevailing in the rocks where the quartz is now found, the liquid contracts and small vapour bubbles (vacuoles) form within the inclusions. These inclusions with their vapour bubbles can be seen under high magnification in nearly all quartz grains and crystals.

If the quartz is slowly heated, the liquid in the inclusions expands to refill the inclusion and the vacuole disappears (the filling temperature). Further heating produces pressure in excess of the tensile strength of the quartz, and the liquid breaks the quartz with a 'pop', that is, the quartz decrepitates. The temperature at which the quartz decrepitates is known as the decrepitation temperature. The difference between the filling temperature and decrepitation temperature is called the over-shoot in temperature.

Three methods have been developed to determine the filling temperature:

1. The original optical method of Sorby (1858), consisting of measuring the diameter of the inclusion cavity and vacuole, converting the relative diameters to relative volumes, thus giving the degree of filling, and utilizing tables of pressure-temperature-volume of water and salt solutions to estimate the filling temperature.

2. A direct optical method utilizing a heating-stage mounted on a high-power microscope through which an operator observes the disappearance of the vacuoles in the inclusions, measuring the filling temperature by thermometer or thermocouple.

3. The decrepitation geothermometer consisting of an electrically heated oven in which a specific quantity of clean crushed (–40+80 mesh) quartz is placed and heated at a controlled constant rate. The miniature explosions or 'pops' of the decrepitating quartz are picked up by a sensitive microphone, amplified, fed to an electronic integrating mechanism and then to a recorder that draws a curve of decrepitation rate vs. time. From this curve the decrepitation temperatures of both primary and secondary inclusions can be read. To determine the filling temperature from these temperatures what is called the over-shoot in temperature must be subtracted. This usually amounts to a few degrees, generally less than 20.

It should be pointed out that the filling temperature of the liquid inclusions does not represent the mineral crystallization temperature that prevailed during the formation of the liquid inclusions. To obtain the crystallization temperature, either an estimated pressure correction or a pressure correction determined by some other geothermal method (e.g., pyrite geothermometer, Smith, 1947) isotopic ratios, etc. must be applied to the filling temperature.

In gold deposits the precise relationship of the gold to liquid inclusions of both primary and secondary origin in associated minerals, mainly quartz, is fundamental to the interpretation of the temperature and other features of deposition of the gold in ore shoots as determined by liquid inclusions or decrepitation methods. This is a problem for which there are no certain answers as all will recognize who have studied the detailed relationships of gold in its deposits. Some general assumptions, however, appear to be valid. In some gold-quartz deposits the gold and the quartz appear to have crystallized nearly contemporaneously. Such deposits are common in younger rocks, but certain (usually paragenetically late) veins in rocks as old as Precambrian also show this feature. In such deposits the temperature and other features of deposition of the quartz as revealed by liquid inclusions and decrepitation probably apply with only slight modification to the deposition of the gold. In many types of gold-quartz deposits of all ages native gold occurs in fractures, crushed zones and small vuggy parts of the quartz. This gold appears to have been deposited during a late stage of the mineralization process. This type of gold is discussed in more detail in an earlier section in this chapter dealing with the associated minerals of gold. Studies of this late gold and the liquid inclusions in the bulk of the quartz indicate that there is probably no relationship between the primary inclusions and the gold; there may, however, be a relationship between the secondary inclusions and the gold, but whether the gold was deposited from the solutions trapped within the secondary inclusions is not certain as the inclusions may have been formed earlier or later than the gold. The writer's (Boyle, 1954) interpretation has been that where gold occurs along fractures now marked by planes of secondary liquid inclusions the gold probably crystallized from the residual solutions trapped in these inclusions.

Machairas (1970*b*) examined the relationship of gold and liquid inclusions in quartz from Guyana; Timmins, Ontario; St Yrieix, France; and elsewhere. He did not distinguish between primary and secondary inclusions, but his figures suggest that both types are present. Nevertheless, he noted a genetic association of gold particles with fluid inclusions containing mainly water and CO_2. In some specimens of quartz he observed gold particles in the liquid inclusion cavities, and further observed that the content of CO_2 in the inclusions in the quartz was greatest in auriferous quartz. As a generality he stated that the concentrations of fluid inclusions and gold in quartz are proportional.

An early investigation of the ore deposition temperature and pressure by decrepitation of quartz and use of the pyrite geothermometer at the McIntyre Mine, Timmins, Ontario by Smith (1948) indicated two separate stages of mineralization in the gold-quartz bodies in greenstones and quartz porphyry, the first extending over the range of 630 to 400°C at a depth of 10 km and the second at 150°C at a much shallower depth. Blais (1954) working with the gold-bearing quartz veins at the O'Brien Mine, northwestern Quebec found by decrepitation methods that the auriferous quartz decrepitated in the temperature range 75 to 120°C, whereas the barren quartz decrepitation began above 130°C. In a recent paper on the O'Brien deposit Krupka *et al.* (1977) optically observed four different types of fluid inclusions: type I – pregold mineralization fluids, CO_2 rich; type II – gold mineralizing fluids showing evidence of boiling at temperature of 380–300°C; type III – postgold mineralization fluids; vapour-liquid two phase inclusions; and type IV – postgold mineralization fluids, halite bearing. Using data on the degree of filling, P-V-T data on the H_2O-NaCl system, and estimates of the depth of mineralization the authors calculated the filling temperatures of the inclusions trapped during the gold mineralization stage (type II) to range from 380 to 300°C. Using similar data the filling temperatures of the other types of inclusions were also estimated: 420 to 250°C for type I inclusions (pregold mineralizing fluids; 75 ± 5% filling); 330 to 170°C for type III inclusions (postgold mineralizing fluids; 85 ± 5% filling); 270 to 140°C for type IV inclusions postmineralizing fluids with NaCl crystals, 90 ± 5% filling). The authors noted that these temperatures are the minimum temperatures of hydrothermal fluids, because the fluids were trapped at pressures greater than those at boiling conditions and pressure corrections must be applied. Furthermore, the uncertainty in the filling temperatures of type I inclusions is probably larger than those shown above, because these inclusions contain liquid CO_2, but they too were assumed to be simple H_2O-NaCl fluids. Despite these uncertainties the authors concluded that the temperatures of hydrothermal fluids at the O'Brien gold deposit gradually decreased toward the later stages of mineralization.

The various results recorded on the geothermal history of the O'Brien deposit mentioned above, point out the great uncertainties in liquid inclusion work. One method (decrepitation) gave an apparent gold deposition temperature of 120 to 75°C, whereas another (degree of filling of inclusions) recorded temperatures of 380 to 300°C. There are in addition uncertainties with respect to leakage of inclusions, pressure corrections, relationship of the liquid inclusions to the actual process of gold deposition and so on. It is obvious that much more sustained research is necessary on the geothermometry of epigenetic gold-quartz veins in order to establish the true temperature limits of gold deposition. The complexities and uncertainties will become even more evident from the results of the following researches.

Boyle (1954) examined the quartz of two gold-bearing shear zone systems (Campbell and Negus-Rycon) by decrepitation methods at Yellowknife, Northwest Territories over a vertical extent of some 1400 ft. Two general ranges of decrepitation were noted 350° to 180°C and 180° to 90°C, the first apparently related to the initial temperature of deposition of the vein quartz and first stage auriferous pyrite and arsenopyrite, and the second probably related to a late stage introduction or to the remobilization and precipitation of gold concentrated during the initial stage of mineralization. More recently Chary (1971), after making a great many assumptions, concluded that the temperature of deposition of the gold-quartz veins in the Con-Rycon Mine at Yellowknife ranged from 350 to 300°C based on sulphur isotope and fluid inclusion studies. The maximum pressure of deposition was estimated at 850 to 900 atm.

At the Lamaque Mine, Bourlamaque, Quebec, Smith (1954) examined the quartz of the No. 6 vein with a view to determining the direction of flow of late stage solutions that probably deposited much of the gold. He found decrepitation temperatures ranging between 80 and 124°C for the quartz.

In recent years Sidorov *et al.* (1971) and Shilo *et al.* (1971) have carried out extensive pressure-temperature research on various types of gold deposits in the northeast U.S.S.R mainly by liquid inclusion methods. Depending on the types of deposits the temperature interval of mineralization ranged from 450 to 50°C, the most productive periods being in the interval 310 to 150°C. The pressure ranged from 5 to 280 atm. Shilo *et al.* give two tables that are of interest to those dealing with various types of gold and gold-silver deposits in plutonic and volcanic terranes. These tables have been slightly modified and are reproduced as Tables 74 and 75.

The so-called epithermal (mainly Tertiary) gold-bearing deposits in New Zealand and United States have recently received attention by means of liquid inclusions and isotopic studies. Robinson (1974) outlined four stages in the mineral paragenesis of the Tui deposit in the Hauraki goldfield of the Coromandel Peninsula: (1) pyrite I + chalcopyrite I + hematite + quartz; (2) galena + sphalerite + quartz, followed by minor pyrite II + chalcopyrite II; (3) minor hematite, barite, cinnabar, kaolinite and carbonates; and (4) cerussite, smithsonite and other supergene minerals. The fractionation of sulphur isotopes between coexisting pairs of minerals indicated temperatures of formation of 400 ± 80°C for pyrite I/chalcopyrite I and 320 ± 60°C for sphalerite/galena. Temperatures derived from quartz, carbonate and barite/water oxygen isotope fractionation showed a gradual decrease from about 250°C at the end of Stage 2, to about 60°C at the end of Stage 3 and about 30°C for the formation of the supergene carbonates. Taylor (1973) concluded from $^{18}O/^{16}O$ isotopic analyses that the Tertiary gold deposits in the Tonopah and Comstock Lode mining districts of Nevada were deposited mainly from heated meteoric waters with temperatures in the range 250 to 300°C; in the Goldfield district much lower temperatures, 125 to 200°C were suggested by the isotopic data. Similar conclusions were drawn for the Tertiary deposits in the Bodie mining district, Mono County, California by O'Neil *et al.* (1973) using oxygen and hydrogen isotope data. They determined that the temperatures of deposition of the gold-silver mineralization fell in the range 215 to 245°C.

Nash and Cunningham (1973) have examined the conditions of deposition of fluorite and gold in the Jamestown district of Colorado. There, fluorite deposits and gold, gold-telluride and lead-silver ores of Tertiary age occur in close proximity. The gold deposits are mainly veins; the fluorite deposits occur principally as disseminations, in breccia zones, stockworks and pipe-shaped bodies in and adjacent to a sodic granite stock. The gold and gold telluride mineralization occurs with and without fluorite in peripheral veins. Liquid inclusions associated with the main fluorite stage were found to have salinities of 26 to 50 per cent and filling temperatures of 250 to 350°C. Two fundamentally different types of fluids were considered to be present in the gold-bearing veins. Inclusions in pregold quartz and fluorite were found to have filling temperatures $\leq 375°C$ and high salinities, suggesting that early quartz and fluorite of the gold-bearing veins were roughly contemporaneous with the main period of fluorspar deposition. Gold and telluride deposition occurred at $< 300°C$. Fluid inclusions most directly associated with gold deposition have filling temperatures ranging from 205 to 270°C and have ~4 per cent salinity, suggesting that the Au-bearing fluids either evolved from the fluorite-bearing fluids or were later unrelated hydrothermal pulses introduced into reopened structures. The occurrence of boiling and the heterogeneity of CO_2 contents were considered to indicate that

Table 74. Characteristics of the gold deposits of the northeastern U.S.S.R.

Association	Type of deposit	Depth of formation	Relationship to magmatic events	Mineral composition	Sulphide content	Temperature interval of mineralization	Temperatures of deposition of productive associations
		(km)			(%)	(°C)	
Plutonic	Gold-rare metal	1.5–2	Genetic with granitoids of orogenic volcano-plutonic associations	Quartz, topaz, tourmaline, wolframite, cassiterite, molybdenite, arsenopyrite, lollingite, minerals of bismuth and cobalt, tellurides of gold and silver	up to 5	450–130	310–160
	Gold-quartz	2–3	Coeval and coextensive with early-orogenic intrusions	Quartz, arsenopyrite, pyrite, sphalerite, galena, gold	up to 1	360–50	250–190
Volcanic	Gold-sulphide	1.5–2	Coextensive with volcanics of andesite composition	Quartz, albite, chalcopyrite, pyrite, galena, sphalerite, tetrahedrite, gold	from 5 to 50	270–150	200–150
	Gold-silver	0.5–1.5	Coextensive with volcanics of liparite-ignimbrite and andesite-basalt composition	Quartz, adularia, calcite, rhodonite, rhodochrosite, dolomite, argentite, sulphosalts of silver, galena, sphalerite, pyrite, marcasite, gold	from 1 to 10	410–50	300–230

Source: Shilo *et al.* (1971).

Table 75. Temperature of formation of gold-silver deposits of northeastern U.S.S.R.

Temperature of formation	Type of deposits	Mineral composition	Content of ore minerals	Temperature interval of mineralization	Temperatures of deposition of productive associations
			(%)	(°C)	
High-temperature	Gold-argentite (with rhodonite)	Quartz, rhodonite, rhodochrosite, argentite, gold, galena, sphalerite, pyrite	up to 1	410–250	up to 400
Medium-temperature	Gold-sulphosalt-argentite	Quartz, calcite, adularia, sphalerite, galena, pyrargyrite, argentite, gold	up to 0.5	325–130	320–290
	Gold-galena-sphalerite	Quartz, calcite, galena, sphalerite, pyrite, marcasite, chalcopyrite, tetrahedrite, argentite, pyrargyrite, gold	up to 10	360–50	300–210
Low temperature	Gold-argentite (with adularia)	Quartz, adularia, fluorite, argentite, aguilarite, galena, sphalerite, pyrite, chalcopyrite, gold	up to 1	240–80	220
	Gold-sulphosalt-stibnite	Quartz, adularia, pyrargyrite, stephanite, polybasite, tetrahedrite, argentite, stibnite	from 1–2 to 50 (in stibnite veins)	270–80	240–220

Source: Shilo *et al.* (1971).

fluid pressures were low and variable, ~150 bar. The fluids were thought to have emanated from an intrusive body at depth.

Nash (1975) concluded from fluid inclusion studies of quartz and sphalerite in vein, pipe and replacement deposits in the northwestern San Juan Mountains, Colorado (Silverton Caldera) that deposition of base metals and gold in the Argentine and adjoining veins (Idarado Mine) essentially took place within a relatively narrow range (280–290°C; corrected for pressure, 305–315°C) from solutions with a low salinity (less than 2 wt. %). The ore fluids appeared to be physically homogeneous liquids over the 3700 ft (1100 m) vertical and 11 200 ft (3400 m) lateral range studied. Other details are elaborated in the original paper.

An investigation of the gold-base metal mineralization at the Sunnyside Mine, Eureka mining district, San Juan County, Colorado by Casadevall (1976) and Casadevall and Ohmoto (1977) revealed six periods of mineralization with their approximate volumetric abundances as follows: (1) pyrite-quartz ores (5%); (2) banded quartz-sulphide ores (30%); (3) massive galena-sphalerite-chalcopyrite-bornite-hematite ores (40%); (4) gold-telluride-quartz ores (1–2%); (5) manganese ores (20%); and (6) quartz-fluorite-carbonate-sulphate ores (5%). These ores fill faults and fractures associated with the upper Oligocene

San Juan–Uncompahgre calderas and were emplaced between 13.0 and 16.6 m.y. ago. Heating studies of fluid inclusions in quartz, fluorite, and rhodochrosite indicated temperature ranges of 250 to 320°C for period (1) to (5) mineralization and 170 to 245°C for period (6) mineralization. Evidence of boiling of period (6) fluids at 240°C was observed from samples collected at 3800 m elevation. These data together with the P-V-T data of dilute salt solutions and a maximum erosion rate of 17cm/1000y indicated P_{H_2O} of between 110 and 220 bars for periods (1) to (5) and about 35 bars for period (6). The ore-forming fluids were essentially water with a small proportion of CO_2 in which were dissolved K, Na, Ca, Cl, oxidized sulphur species such as HSO_4^-, KSO_4^- and $NaSO_4^-$, and the metals including Cu, Fe, Zn and Mn at concentrations ranging from less than 10 to 1000 ppm. The pH of periods (1) to (5) fluids ranged from 4.3 to 5.9. In the last part of their paper Casadevall and Ohmoto, drawing on isotope date for O, H, S and C, conclude that the mineralizing solutions were essentially meteroric water and that the sulphur and metals came from the country rocks in the vicinity of the deposit (Mesozoic and/or Paleozoic marine sediments provided the various salts and sulphur and the Tertiary volcanic rocks and Precambrian basement rocks the metallic elements such as lead, zinc, gold, etc.).

In U.S.S.R. a number of studies of the temperature of deposition of epithermal (volcanic class) gold-silver deposits have been done. The work of Naiborodin and Goncharov (1970) on the Agatovskoye deposit in Cretaceous-Paleogene volcanics in the southern part of the Okhotsk-Chukotka volcanic belt may be mentioned here. The mineralization is in veins carrying essentially quartz, carbonates, barite, galena, sphalerite, chalcopyrite, pyrite, marcasite, arsenopyrite, argentite, pyrargyrite and gold (electrum). The veins are of four types: (1) quartz, (2) carbonate-quartz, (3) sulphide-carbonate-quartz, (4) sulphide-carbonate stage and (5) barite-opal-chalcedony stage. The study of gaseous-liquid inclusions indicated that the Agatovskoye deposit formed within a temperature range of 365 to as low as 50°C. The deposition of ore minerals took place between 300 to 200°C. Native gold was deposited between 250 and 230°C. The temperature changed sharply during the process of mineralization, which was accompanied by temperature inversions of 100 to 150°C between the stages. These conditions were explained by the authors as due to internal changes of thermodynamic conditions, mixing of high temperature fluids with meteoric water and as a result of the effect on the temperature regime by subvolcanic intrusions.

The temperature of formation of the so-called subvolcanic gold-silver deposits in central Kamchatka has been studied by Andrusenko and Shchepotyev (1974) by means of liquid inclusion thermometry. The results indicated that the following types of mineralization formed at the given temperatures: (a) copper-molybdenum mineralization precipitated from highly concentrated essentially chloride solutions within the temperature range of 340 to 70°C; (b) gold-silver mineralization precipitated from alkaline chloride-sulfate-bicarbonate solutions with carbon dioxide in the ranges of 400 to 300°C (early gold), 320 to 240°C (main gold concentrations), 260 to 115°C (late segregations); and (c) mercury mineralization in the temperature range 260 to 105°C.

In Japan, Hattori (1975) carried out a detailed geochemical investigation of the Yatani Mine, a representative of the epithermal precious and base metal deposits of Tertiary age that occur mainly in Neogene volcanics in the so called Green Tuff region. The Yatani deposits occur as fissure fillings and are divided into two types – lead-zinc veins and gold-silver veins. All of the veins exhibit breccia, cockade or crustified banding structures with occasional druses. The major constituent minerals of the lead-zinc veins are sphalerite, galena, chalcopyrite, pyrrhotite, marcasite, quartz, iron chlorite, muscovite, adularia, Mn-silicate and manganiferous carbonate with minor amounts of arsenopyrite, stannite, electrum and argentite. The gold-silver veins are Ginguro bands composed essentially of sphalerite, galena, chalcopyrite, electrum, argentite, pyrite, quartz and adularia with minor amounts of cassiterite, stannite, marcasite, montmorillonite, iron chlorite and manganiferous carbonate. Using various geochemical parameters Hattori estimated the environmental factors of the two types of veins as follows: temperature of formation was 250 to 200°C for the Au-Ag veins and approximately the same for the Pb-Zn veins; the sulphur fugacity was 10^{-11} atm at 250°C to 10^{-13} atm at 200°C for the Au-Ag veins and 10^{-12} to 10^{-14} atm at 250°C or 10^{-14} to 10^{-16} atm at 200°C for the Pb-Zn veins; and the oxygen fugacity was $10^{-34.5}$ to 10^{-39} atm at 250°C or $10^{-37.5}$ to 10^{-42} atm at 200°C for the Au-Ag veins and 10^{-37} to 10^{-40} atm at 250°C or 10^{-40} to $10^{-45.5}$ atm at 200°C for the Pb-Zn veins. Regarding the chemical characteristics of the ore-forming solutions Hattori (1975) concluded that they had an NaCl equivalent concentration of 0.1 to 0.2 mol/L; a pH, about 6 or more for the Au-Ag veins and 6 or less for the Pb-Zn veins; a concentration of total dissolved sulphur equal to 10^{-3} to 10^{-2} mol/L; the dominant dissolved sulphur species for the Pb-Zn veins was hydrogen sulphide, whereas the Au-Ag veins were formed near the boundary separating dominant sulphate ion from hydrogen sulphide.

Hattori (1975) further concluded that the gold was mainly transported as gold-sulphur complexes rather than as gold-chloride complexes, and that the precipitation of gold was mainly caused by an oxidation process. Coprecipitation of sphalerite and galena with gold he thought would be expected in neutral or weakly alkaline solution with low salinity and total dissolved sulphur of 10^{-2} mol/L when the fugacity of oxygen increased as a result of the rising of the ore solution and when the breakdown of the metal-sulphur complexes occurred.

Czamanske *et al.* (1973) have used annealing history phenomena (interdiffusion in the Au-Ag system) in natural gold to estimate upper limits of gold deposition. Concentration changes of up to 30 weight per cent Ag indicate probable deposition temperatures of less than 300°C for electrum from Copper Basin, Arizona and Alder Gulch, Montana. The gold in the Homestake Mine, South Dakota probably was formed at temperatures well below 400°C.

The sphalerite geothermometer has been used by a few investigators to estimate the temperature of deposition of sphalerite-pyrrhotite in gold deposits, but the results have been quite erratic. At Keno Hill the temperatures obtained seemed to be at variance with the geological situation, and the method was deemed not to be applicable to the various deposits (Boyle and Jambor, 1963).

According to Clark (1960) and Kretschmar (1973) the composition of arsenopyrite varies with temperature. This is the basis of the arsenopyrite geothermometer, and precise temperatures can generally be obtained if an estimate of the sulphur fugacity prevailing at the site of deposition can be made from various coexisting minerals. Since arsenopyrite is a common associate of gold, the composition (as measured from certain interplanar spacings by X-ray diffraction) of the sulphide-arsenide may be useful in estimating the formation temperatures particularly of the early stage of deposition of some gold deposits (the gold-arsenopyrite-pyrite stage noted in the next section dealing with paragenesis). The temperature of formation of later stages can also be estimated, if arsenopyrite is present in the mineral assemblage.

The temperature of formation of arsenopyrite in the gold-quartz deposits of the Yenisei Ridge has been investigated by Li *et al.* (1971) by means of X-ray diffraction measurements. The temperatures obtained ranged from 350 to 575°C. A correlation was noted between the temperature of formation of the arsenopyrite, its morphology and the distance of its host deposit from a large granitic intrusion; in general higher temperatures were noted for those deposits near the intrusive and lower temperatures for those distant from the intrusive.

Summarizing the data on gold-quartz deposits we can say that the deposition of the bulk of the quartz and sulphide mineralization took place within the interval 500 to 150°C. There is considerable evidence to support the thesis that much of the gold in many deposits was deposited (or mobilized from pre-existing auriferous sulphides, etc. and redeposited) within the interval 150 to 75°C. In some deposits higher temperatures for the deposition of gold seem probable, usually in the range 300 to 150°C. The range of pressure appears to be from about 2 bars for near surface gold-quartz deposits to 300 bars for deep seated deposits.

Relatively little work has been done on the geothermometry and geobarometry of auriferous skarn type deposits. Our limited results based on decrepitation and liquid inclusions suggest temperatures of formation of skarn minerals to range from about 350 to 700°C and the temperature of deposition of quartz associated with gold in these deposits to range from 100 to 350°C. Shcherbakov *et al.* (1972) investigated the skarn-type gold deposits in the Sinyukhinsk district of the Altai and found that the quartz subjected to skarnification gave a temperature range of 420 to 780°C by liquid inclusion methods; the garnet registered 420 to 700°C. Quartz associated with the gold stage gave temperatures ranging from 88 to 350°C by liquid inclusion methods. The pressures at which skarns and their associated gold mineralization form must vary widely depending on their depth of formation; probably the pressures vary from a few hundred bars to 5 kbars or more for most deposits.

The pH conditions of the migration and deposition of gold are discussed at length in Chapter II. There it was concluded that the solutions that deposited gold in epigenetic deposits were mainly neutral to slightly alkaline, a situation supported by data on natural waters that are now depositing gold and by data on wall-rock alteration effects noted in many gold-quartz deposits. Acid solutions may have been responsible for the deposition of gold where minerals such as alunite were developed.

Paragenesis and zoning in epigenetic gold deposits. The paragenesis of the various minerals in epigenetic gold deposits as determined by microscopic methods and the observations of crosscutting veinlets is reasonably constant, although there are commonly reversals in the sequences and other complications that need not concern us here. The major elemental and mineral paragenesis (oldest to youngest stages) in most epigenetic gold deposits are given below and diagrammed in Figure 93. Not all stages or elements are present in any one deposit. Elements and minerals in parentheses are rare in the respective stage.

1. Fe, (Ni), (Co), S, As, SiO_2, Ca, Mg, Mn, K, Na, CO_3, C, Au and Ag represented mainly by pyrite and/or arsenopyrite essentially coeval with quartz and carbonates. Marcasite may occasionally accompany or take the place of pyrite in some deposits, especially those formed near the surface. Pyrrhotite is commonly a later mineral in this stage but is generally rare in most deposits except those formed under deep-seated conditions or in iron-formations in which case it takes the place of pyrite. In some deposits pyrrhotite accompanies or follows Stage 3. Gold and silver are lattice constituents of pyrite and/or arsenopyrite, or the two precious metals occur in submicroscopic and microscopic particles of native gold in the sulphide minerals of this stage. Where Ni-Co arsenides are present, they appear to be about the same age as arsenopyrite. Carbon (graphite) is usually introduced at this stage, although in places the substance is late occurring along late fractures and slips. The bulk of the feldspars and sericite are generally formed during this stage; some chlorite is introduced.

2. W. Mo, (Sn) and S represented by wolframite, scheelite and (cassiterite). In some deposits these minerals are contemporaneous or nearly so with those in Stage 1. Molybdenite is a late mineral of this stage in some deposits.

3. Mo, S represented by molybdenite. In most deposits molybdenite appears to be an early mineral, but in some deposits there are late generations of the mineral.

4. Bi, S represented by native bismuth, bismuthinite, etc. Two generations of these minerals are apparent in gold deposits. In some deposits only an early generation is present; in others only a late generation (Stage 11); and in still others both generations.

5. Zn, Cd, (Au), (Ag), S represented by sphalerite. Au and Ag are usually only minor constituents of this phase.

6. U, Th and rare earths represented by uraninite (pitchblende) and/or brannerite. In some deposits uraninite is coeval with Stage 7; in others the uraniferous mineralization follows Stage 13.

7. Cu, S, As, Sb, Au and Ag represented mainly by chalcopyrite, tennantite, tetrahedrite, enargite, cubanite and bornite. The paragenesis of these copper minerals is often complicated. In some deposits tetrahedrite precedes chalcopyrite; in others the reverse is true. Gold and silver are lattice constituents of the copper minerals or occur in submicroscopic and microscopic particles of gold in the sulphides and sulphosalts.

8. Pb, Ag, Au, (Bi), S represented by galena. Silver is a lattice constituent of galena or occurs in a variety of exsolved (?) silver minerals. The position of gold is uncertain; it may be a lattice constituent or may occur as exsolved (?) native gold

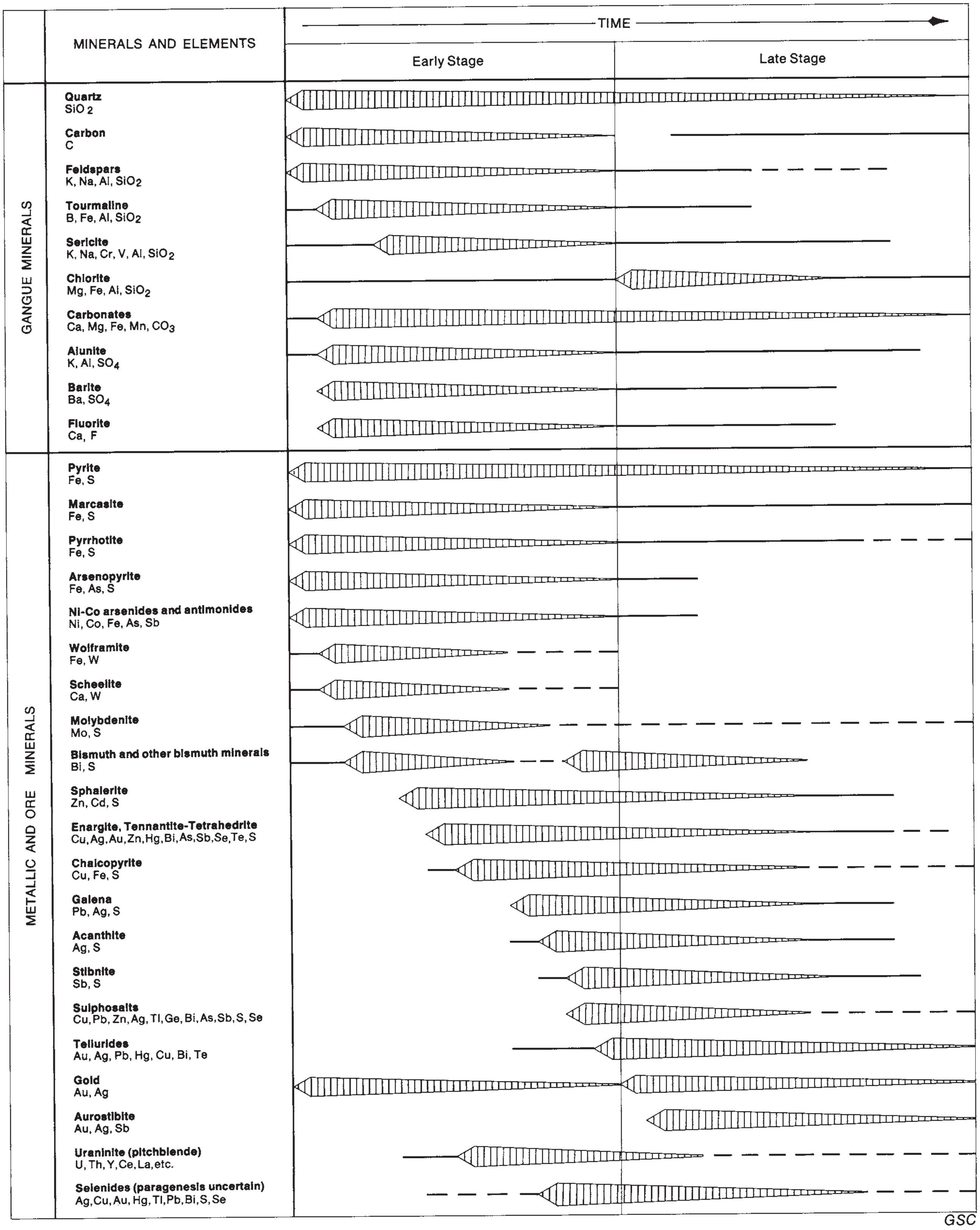

Figure 93. Generalized paragenetic sequence of principal minerals and elements in epigenetic gold deposits. Minerals and elements shown include only those in veins, lodes, etc.; minerals and elements in wall-rock alteration zones are excluded.

or gold tellurides in the galena.

9. Ag, S represented by acanthite (argentite).

10. Sb, (As), S, (Se), Fe, Cu, Zn, Pb, Bi, Ag, Au represented by stibnite and various sulphosalts, e.g., pyrargyrite. Gold and silver may be lattice constituents of these minerals or may occur in native gold as inclusions in the minerals. The paragenesis of these minerals is often complicated, but stibnite commonly precedes the sulphosalts in many deposits. In other deposits it is coeval with the antimony sulphosalts.

11. Bi, Ag, Au, S represented by native bismuth and bismuthinite. The gold and silver may occur in native gold intimately intergrown with native bismuth or the precious metals may occur in the mineral maldonite.

12. Au, Ag, Pb, Hg, Cu, Bi, Te represented by the precious and base metal tellurides. Commonly the tellurides are paragenetically older than native gold, but in some deposits they all appear to be coeval.

13. Au, Ag represented by native gold and electrum.

14. Au, Ag, Sb represented by aurostibite.

15. Hg, As, S, (Te) represented by cinnabar, orpiment and realgar and in places by mercury tellurides. The exact paragenesis of orpiment and realgar in gold deposits is uncertain. Both are late minerals, and in some veins they may slightly precede the gold. More generally, however, these minerals are paragenetically coeval with gold or younger.

The exact position of the mercury minerals is uncertain; they are, however, invariably late in the paragenetic sequence. The position of gold is not constant; it appears in a number of the stages commonly being precipitated throughout all stages in some deposits. In many deposits there is much gold in the early pyrite and arsenopyrite and some gold in the sphalerite, chalcopyrite, galena and sulphosalts. In most deposits, however, the largest amounts of free gold, electrum and gold tellurides are the last minerals to crystallize. Aurostibite is generally closely associated with native gold and in some deposits is paragenetically later than the metal, rimming or veining it. In other deposits aurostibite and native gold appear to be coeval. Aurostibite appears to occur only in deposits that are relatively enriched in antimony, and in some deposits the mineral appears to accompany Stage 10. There is commonly a close paragenetic relationship between gold and native bismuth and bismuthinite as well as with a great variety of other bismuth-bearing minerals. In most deposits the gold minerals are slightly later than the bismuth minerals or intimately mixed with them indicating nearly contemporaneous deposition. In some gold deposits bismuth follows lead and is precipitated in galena apparently as a lattice constituent in some cases. Galena may also contain bismuth in the form of minute inclusions of minerals such as matildite ($AgBiS_2$) and aramayoite ($Ag(Bi,Sb)S_2$). There are reports in the older literature of the occurrence of bismuthinite following sphalerite (Stage 5), but I have not been able to verify this microscopically. Molybdenite presents a varied habit in gold deposits. In some deposits it appears as an early mineral; in others it is late occurring along late slips. The tungsten minerals are invariably early minerals. Scheelite commonly appears to be about the same age as the carbonates in skarn deposits and gold-quartz veins. This apparent contemporaneity may, however, be due to the fact that the tungsten radical has replaced the carbonate radical ($CaCO_3 + WO_4^{2-} = CaWO_4 + CO_3^{2-}$) in which case the scheelite is paragenetically later than the carbonates. Wolframite is generally later than pyrite, pyrrhotite and arsenopyrite and earlier than the Zn, Cu, Pb and Ag sulphides and sulphosalts and the late gold minerals. Cassiterite, when present in deposits, is invariably paragenetically older than native gold and other gold minerals. The position of barite and fluorite in the sequence is uncertain and seems to be variable from deposit to deposit. Commonly the two minerals accompany the intermediate quartz and carbonate stages. In some deposits, however, they are relatively older than native gold and other gold minerals. Alunite exhibits a similar behaviour, although it is usually an early mineral and seems to accompany the pyrite stage in some deposits. Feldspars are generally early minerals in the paragenesis usually being mainly deposited during Stage 1; some deposits have several ages of feldspar. Quartz and the various carbonates are invariably early minerals in the paragenetic sequence, and it is notable that they continue to be deposited continuously or intermittently throughout the paragenetic stages manifest in epigenetic gold deposits. Sericite and chlorite may be deposited throughout the paragenesis but usually only in small amounts after Stage 1. Excepting some auriferous skarns, magnetite is a relatively rare gangue mineral in most deposits. In a few vein deposits magnetite can apparently take the place of pyrite and/or pyrrhotite as in the Ust'-Kara gold belt in eastern Transbaikal, U.S.S.R. (Kolosova and Onishchuk, 1971). In these deposits the gold and magnetite, which are paragenetically early minerals in a second stage of mineralization, are coeval or nearly so. Certain of the auriferous veins in Chile are also rich in magnetite and specularite, which appear to be early minerals in the paragenesis. Most of the auriferous deposits containing magnetite and/or hematite occur in granitic intrusives or in high grade metamorphic terranes. Those at Tennant Creek, Northern Territory, Australia are, however, in relatively low grade metasediments (Large, 1975). In some deposits uraninite (pitchblende) and brannerite are distinctly earlier in their paragenesis than gold and gold tellurides. Their maximum deposition appears to precede chalcopyrite but in some deposits is coeval with this mineral. In other deposits veins carrying pitchblende are distinctly later than auriferous veins in the same lode system (e.g., Box Mine, Goldfields, Saskatchewan). The position of the various selenides is uncertain. These minerals are generally late in the paragenetic sequence and appear to overlap the deposition of chalcopyrite and galena with the maximum deposition taking place during the sulphosalt–telluride stages.

In conclusion it should be recognized that the successive stages noted above are rarely sharply demarkated either in time or space. There is much overlapping, telescoping, repetition and omission of some of the stages. A more detailed discussion of the paragenetic relationships of minerals to native gold and other gold minerals is given in previous sections on the elemental and mineral associates of gold.

A sequence (zonation) of elements and minerals horizontally outward from intrusive granitic bodies or granitization centres is commonly observed as shown in Figure 94 and Table 76. This zonation was noted by a number of early investigators and elaborated upon by Spurr (1923) and

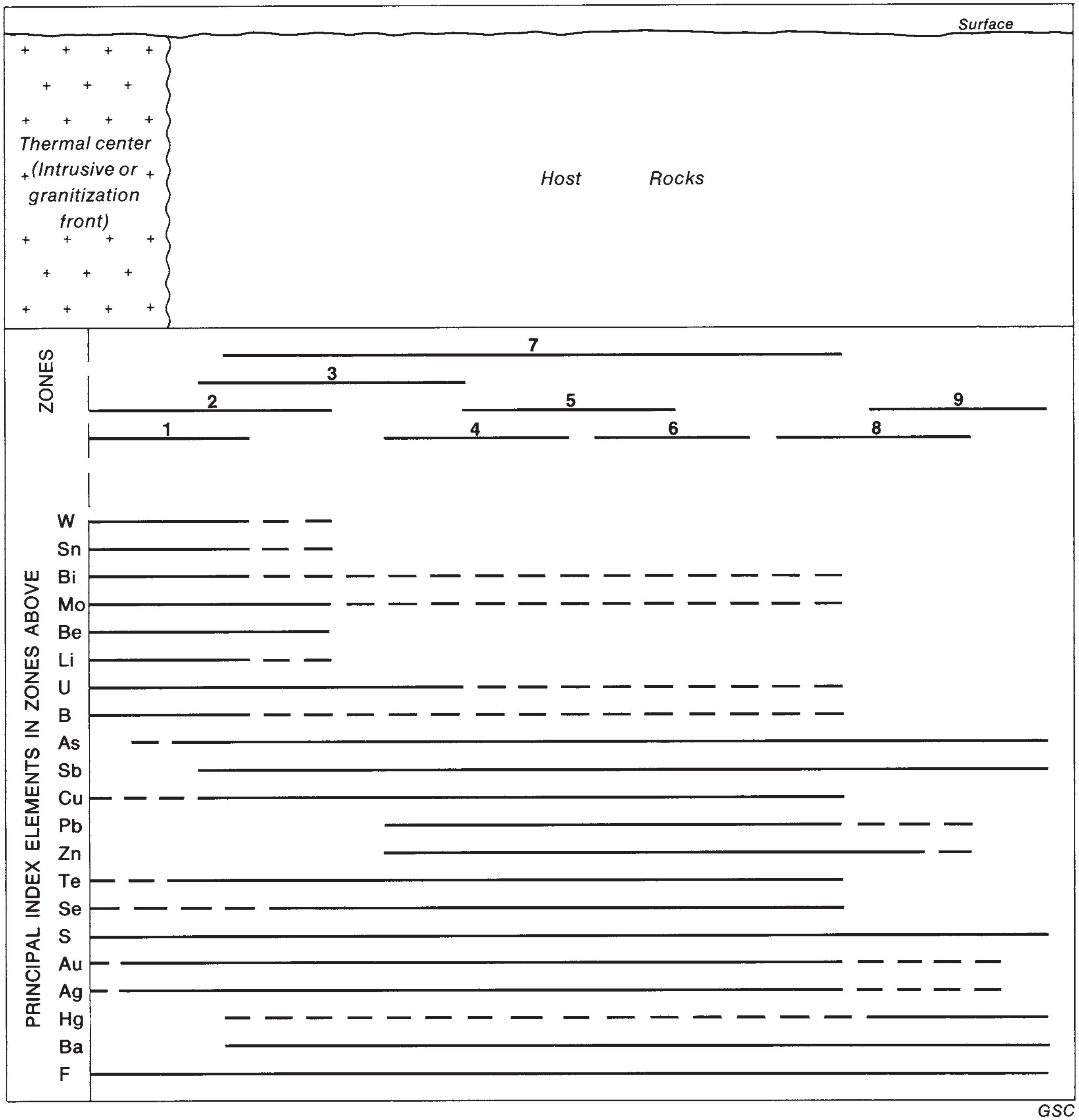

Figure 94. Generalized horizontal endogenic zonation of elements outward from a thermal centre. Elements shown include only those in veins, lodes, etc.; elements in wall-rock alteration zones are excluded (*see also* Table 76).

Contents

Table 76. Generalized horizontal endogenic zonation of elements and minerals outward from a thermal centre*

Zone	1	2	3	4	5	6	7	8	9
Persistent elements	SiO_2, Fe, S	SiO_2, Fe, Ca, Mg, Mn, S	SiO_2, Fe, Ca, Mg, Mn, S	SiO_2, Fe, Ca, Mg, Mn, S	SiO_2, Fe, Ca, Mg, Mn, S	SiO_2, Fe, Ca, Mg, Mn, S	SiO_2, Fe, Ca, Mg, Mn, S	SiO_2, Fe, Ca, Mg, Mn, S	SiO_2, Fe, Ca, Mg, Mn, S
Index elements	W, Sn, Mo, Bi, Be, Ta, Nb, Li, F, RE†, Th, Zr, U, B, As, S, (Cu)	Fe, S, As (Sb), (Te), Au, Ag, Cu, Mo	Cu, S, As, Sb Au, Ag, Te, U	Zn, Cd, S (Au), (Ag)	Pb, Ag, Au, S, Te	Ag, S, (Au)	Sb, As, S, Cu, Zn, Pb, Bi, Ag, Au, Fe, Te, Se	As, Sb (Au), (Ag), (H_g)	Hg, (Sb), (As)
Au/Ag ratio	High	High		Intermediate	Intermediate		Low	Low	
Persistent minerals	Quartz, feldspar, micas, pyrite, pyrrhotite, (magnetite and/or hematite may take the place of pyrite in some deposits)	Quartz, feldspar, pyrite, pyrrhotite, carbonates. (Magnetite and/or hematite may take the place of pyrite in some deposits)	Quartz, feldspar, pyrite, pyrrhotite, carbonates	Quartz, pyrite, pyrrhotite, carbonates	Quartz, pyrite, carbonates	Quartz, pyrite, marcasite, carbonates	Quartz, pyrite, marcasite, carbonates	Quartz, pyrite, marcasite, carbonates	Quartz, chalcedony, pyrite, marcasite, carbonates
Index minerals	Wolframite, scheelite, cassiterite, arsenopyrite, molybdenite, bismuth, bismuthinite, topaz, beryl, tantalite-columbite, uraninite and various other rare metal minerals	Arsenopyrite Ni-Co arsenides and antimonides, molybdenite, native gold, scheelite	Chalcopyrite, tennantite-tetrahedrite, enargite, barite, fluorite, uraninite (pitchblende)	Sphalerite, barite, fluorite	Galena, tellurides, barite, fluorite	Acanthite	Stibnite, sulphosalts, barite, fluorite	Realgar, orpiment, stibnite, barite, fluorite	Cinnabar, realgar, orpiment, stibnite, barite, fluorite
Remarks	Mineralization commonly in the intrusives and their border zones. Deposits are generally not auriferous. Includes pegmatites	Contact metamorphic deposits may carry copper minerals such as bornite, chalcocite, molybdenite, etc. Some desposits may be in intrusive thermal centre (porphyry Cu-Mo deposits)	May overlap zone 2	May coalesce with zone 5	May coalesce with zone 4	May coalesce with zones 4 and 5	May overlap zones 3–6	May overlap zone 7. Some veins and replacement deposits carry gold	May overlap zone 8. Rarely auriferous

*See also Figure 94.
†RE = rare earths.

Emmons (1924). Perused carefully the zonation sequence from granitic body outwards is essentially the same as the elemental and mineralogical paragenetic sequence of oldest to youngest. Yet another type of zonation is found in some deposits in fractures and faults that cut deeply into the earth. This is a vertical zonation of elements and minerals (Fig. 95) noted in a general way by a number of early investigators and later discussed in detail by Spurr (1923), Emmons (1924), Lindgren (1927, 1937) and Graton (1933). This type of vertical zonation is manifest most clearly in Tertiary deposits; it is not marked in Precambrian deposits, some of these extending to depths of 10 000 ft (Kolar) or more without decrease in gold content and radical change in the mineralization or with a very gradual change from pyrite to pyrrhotite and diminution of minerals such as stibnite and sulphosalts. The reason for this difference is not clear; one can speculate that the Tertiary deposits were precipitated under a steep thermal gradient, whereas the thermal gradient during the deposition of the Precambrian deposits would appear to have been gentle or practically nonexistent. In general, the vertical zonation in gold deposits where present is similar to the paragenetic sequence and lateral zonation.

It should not be assumed, however, that all auriferous deposits exhibit a regular vertical zonation as shown in Figure 95. Most deposits show a general tendency toward the ideal, but some diverge widely from it. Even some Precambrian deposits exhibit a complex vertical zonation. Large (1975) describing the zonation at the Proterozoic Juno Mine in the Tennant Creek goldfield, Central Australia gives a complex vertical sequence in this small but rich gold lode. Both the gangue minerals and ore minerals are vertically zoned.

The nature of the gold in deposits commonly exhibits differences with respect to proximity to igneous bodies. Numerous deposits near granitic bodies have relatively little free gold, the element being intimately bound in pyrite or arsenopyrite as a lattice constituent or in a very finely divided form. On the other hand deposits at a distance from the intrusives generally have increasing quantities of free crystallized gold. There are, however, numerous exceptions to these generalizations. The Au/Ag ratio of deposits as a whole may show a pattern, the deposits next to granitic and other igneous bodies having a higher ratio that decreases with distance from the igneous bodies. This is obviously due in some places to the increase in silver minerals with increasing distance from the igneous bodies. The Au/Ag ratio (fineness) of native gold, likewise, appears to show the same relationship in some belts, although there are many aberrations. Commonly, there is no pattern, or a complex or erratic one exists. However, in certain deposits formed near the surface (Tertiary epithermal deposits), the early gold in pyrite and arsenopyrite is frequently silver deficient (850 or more fine), whereas late crystallized gold is usually silver rich (800 fine or less) in the same deposit. Deep seated deposits do not generally show this tendency; in fact in certain Precambrian (Archean) deposits the reverse obtains. The reason for this may be subsequent recrystallization of the early auriferous pyrite and arsenopyrite resulting in the migration of gold and silver (*see below*). Vertical zonations in the Au/Ag ratio of deposits have also been noted. (*See also* the section on Au/Ag ratios in this chapter.) Probably, in the majority of deposits the Au/Ag ratio increases with depth, a circumstance due, it is thought by a number of investigators, to the relatively high mobility of silver, which compared with gold, tends to migrate (diffuse) out of the higher temperature zones.

The trace elemental content of gold in deposits may exhibit zonal variations. Thus, in some deposits elements such as antimony and mercury may be much more abundant in the free gold near the surface than at depth. This is especially true in certain Tertiary deposits and seems to be true in some Precambrian deposits. Similarly the free gold in deposits in and near thermal centres (intrusive granites, etc.) is commonly impoverished in elements such as antimony and mercury compared with the gold in deposits distant from the centres.

There are many exceptions to the statements made above about the fineness of native gold and the trace element content of the metal. The cause of some of these exceptions is not readily ascertained in some deposits; in others the cause seems to be predicated on the type of wall rock. As noted in an earlier section ore shoots in acidic wall rocks tend to have much lower Au/Ag ratios, and in some cases the gold also appears to have a lower fineness than in shoots developed in basic rock. In addition, subsequent processes of recrystallization and migration of gold and silver after the initial deposition of the two metals obviously has an effect in some, generally deep-seated, deposits. All of these features require further detailed research.

The precise causes of the relatively consistent paragenetic sequences and zonations has eluded the geologist and chemist for more than a century due to the enormous chemical complexity of the ore-forming processes. Early investigators concluded that the phenomena were due predominantly to temperature effects; later investigators assumed a single ore solution or mineralization stage and considered that the determining factors were due to hardness of minerals, power of crystallization of minerals and abundance of mineral constituents (Gilbert, 1924); solubilities of ore and gangue minerals (Newhouse, 1928; Verhoogen, 1938); progressive change in anion/cation ratio as mineralization proceeded (Bandy, 1940); impedance of structures (MacKay, 1946); volatility of ore constituents (Brown, 1948); metallic melting point (Sullivan, 1954); relative amounts of ionic and covalent bonding in sulphides (Ringwood, 1956); increase in chemical potential of sulphur (McKinstry and Kennedy, 1957); relative stability of covalent-bonded complex ions (Barnes, 1962); chalcophile element abundances (Taylor, 1963), polar-covalent bond stabilities (Pasquali and Bisque, 1975); and chemical affinities and acidity–basicity indicators (Marakushev, 1977). Polyascendent solutions have also been assumed. A number of investigators now think that zoning and the paragenetic relationships are the result of pulsation processes of mineralization punctuated in places by structural activities such as the reopening of fractures or formation of faults and fractures with different orientations or at successively greater distances from intrusive or granitization centres. There are also the effects of wall rocks on zoning to consider. These effects are partly structural and partly chemical. It is evident in some areas that certain rocks form extensive dilatant zones whereas others do not; similarly there is commonly a differential effect on the precipitation of elements exerted by different types of host rocks. For example, acidic solutions are more profoundly

ZONE	SURFACE	Au/Ag RATIO	PERSISTENT ELEMENTS	INDEX ELEMENTS	PERSISTENT MINERALS	INDEX MINERALS	REMARKS
1			SiO_2, Fe, Ca, Mg, Mn, S	Ba, Sr, F	Quartz (chalcedony), pyrite, marcasite, carbonates	Barite, fluorite, (cinnabar)	This zone is rare in most veins. Generally barren of gold and silver
2			SiO_2, Fe, Ca, Mg, Mn, S	Hg, Sb, As, Ba, Sr, F	Quartz (chalcedony), pyrite, marcasite, carbonates	Cinnabar, realgar, orpiment, stibnite, barite, fluorite	In certain veins this zone may be auriferous and argentiferous
3		Low	SiO_2, Fe, Ca, Mg, Mn, S	Ag, Au, As, Sb, Cu, Zn, Pb, Bi, Te, Se	Quartz (chalcedony), pyrite, carbonates, galena, sphalerite, chalcopyrite, gold (electrum), (molybdenite)	Acanthite, gold, stibnite, sulphosalts, tellurides, selenides, bismuthinite and other bismuth minerals, adularia, alunite, Mn-silicates, Mn-carbonates, fluorite, barite, (scheelite), (wolframite)	Constitutes bonanza section of most epithermal gold-silver deposits. Passes with decrease in gold and silver into zone 4. Generally absent in deep-seated deposits.
4			SiO_2, Fe, Ca, Mg, Mn, S	Cu, Zn, Pb	Quartz, pyrite, carbonates, galena, sphalerite, chalcopyrite	Chalcopyrite, pyrite, sphalerite, galena, barite	Commonly low or barren in gold and silver, Represents the bottoms of many epithermal Au-Ag veins.
5	VEIN OR LODE	Medium	SiO_2, Fe, Ca, Mg, Mn, S	Au, Ag, Cu, Pb, Zn, As, Sb, Te,	Quartz, pyrite, arsenopyrite, carbonates, galena, sphalerite, chalcopyrite, gold, (molybdenite)	Galena, sphalerite, tetrahedrite-tennantite, (acanthite), sulphosalts, (scheelite), (wolframite), tellurides, gold	Sphalerite commonly increases with depth.
6			SiO_2, Fe, Ca, Mg, Mn, S	Au, Ag, Cu, As, Sb	Quartz, pyrite, arsenopyrite, carbonates, gold, (molybdenite)	Chalcopyrite, tetrahedrite-tennantite, enargite; uraninite (pitchblende); scheelite, wolframite, tellurides, gold, (tourmaline)	Merges into zone 7
7			SiO_2, Fe, Ca, Mg, Mn, S	Au, Ag, As, Te, Cu, W	Quartz, pyrite, arsenopyrite, carbonates, feldspar, gold, (molybdenite)	Arsenopyrite, chalcopyrite, scheelite, wolframite, tourmaline, tellurides, gold	Merges into zone 8
8		High	SiO_2, Fe, Ca, Mg, Mn, S	Au, Ag, Cu, W	Quartz, pyrite, pyrrhotite, feldspar, carbonates, tourmaline, gold, (molybdenite)	Pyrite, pyrrhotite, chalcopyrite, arsenopyrite, scheelite, wolframite, gold, tourmaline	
9			SiO_2, Fe, S	W, Sn, Mo, Bi, B, F, As	Quartz, feldspar, pyrite, pyrrhotite, molybdenite	Pyrite, pyrrhotite, bismuth, molybdenite, arsenopyrite, bismuthinite, wolframite, scheelite, cassiterite, tourmaline, topaz	Generally barren of gold and silver

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Figure 95. Idealized vertical endogenic zonation of elements and minerals in epigenetic gold deposits. Minerals and elements shown include only those in veins, lodes, etc.; minerals and elements in wall-rock alteration zones are excluded.

affected (neutralized), and the processes of ore formation more radically changed by reaction with limestones than they are with schists and shales. With respect to gold deposits there is also a marked effect on the Au/Ag ratio exerted by acidic and basic wall rocks as mentioned in a previous section in this chapter.

Probably all of the factors mentioned above are involved to some extent in zoning, but we shall not pursue any of them in detail here. General reviews of the various suggested mechanisms of zoning can be found in the papers by Lindgren (1927), Park (1955), Barnes (1962) and Petrovskaya *et al.* (1974) and in the volumes edited by Kutina and Stemprok (1963–1965) and Sokolov (1974). Finally, to conclude this review of the literature, it is of interest to note that Ewers and Keays (1977) observed a crude metalliferous zoning in present day auriferous hydrothermal systems in the Broadlands geothermal field, New Zealand. They noted that the elements As, Sb, Au and Tl are enriched in the near surface parts of the system whereas Ag, Se, Te, Bi, Pb, Zn, Cu and Co are concentrated mainly at depth. They concluded that the deposition of T1 occurs primarily in response to decreasing solution temperatures, while the other elements are precipitated through the combined effects of decreasing temperatures and boiling of the hydrothermal solutions within permeable horizons. Oxidation reactions and changes in pH resulting from solution/wall-rock interactions were considered unlikely to have influenced deposition to any great extent. For those elements believed to be transported as thio complexes (i.e., As, Au and Sb), the decrease in pressure as solutions are discharged at the surface and resulting losses of H_2S through boiling reduced the stabilities of these complexes and contributed to the surface enrichment of As, Au and Sb.

In considerations of zoning of mineral deposits both solution and diffusion effects must be taken into account. Where the systems are relatively simple and mineral deposition has apparently taken place at low temperatures from solutions that permeate faults and fractures, it appears that the paragenetic (deposition and replacement) sequence can be related in a crude way to the solubilities (solubility products) of carbonates, sulphates and sulphides as shown by the writer (Boyle, 1972) for the barite-sulphide mineralization at Walton, Nova Scotia. When gold deposits are considered, however, there are many more factors involved in paragenesis and zoning than solubilities in aqueous solutions. In auriferous deposits the role of diffusion of constituents is important as are also extensive wall-rock alteration reactions and remobilization processes involving gold initially deposited in sulphides subjected to post-depositional structural deformation (crushing, shearing and recrystallization). Each of these complex problems are dealt with in turn.

The migration of ore and gangue constituents in any form is the result of differences in chemical potential (μ) of a constituent (component) between its source and site of deposition. For the migration of a constituent to take place in thermodynamic terms the following condition must obtain:

$$\mu \text{ (deposition site)} < \mu \text{ (source)}$$

and at equilibrium when no migration takes place:

$$\mu \text{ (deposition site)} = \mu \text{ (source)}$$

The first is the fundamental thermodynamic law governing the flow of constituents (components) by diffusion, gaseous flow or other modes of transport. If we could evaluate the chemical potentials of ore and gangue constituents there would be no difficulty in explaining the zonal and paragenetic features of mineral deposits. Unfortunately, at our state of knowledge, this cannot be done, and a moment's reflection on the thermodynamic principles of chemical potentials and endogenic geological phenomena will indicate why.

Simply stated the chemical potential of a constituent (component), μ, is a function of the concentration (activity), C, of a constituent, the volume of the constituent and hence the external pressure on the system, P, and the temperature, T. This is usually stated as:

$$\mu = f(C, P, T)$$

In any endogenic system it is sometimes possible to estimate the temperature between source and site of deposition; the pressure, likewise, may be estimated from the load of superincumbent rocks, or differences in pressure can be estimated from the fact that the pressure commonly approaches zero in a dilatant zone, whereas outside the zone it is equivalent to the load of superincumbent rocks, neglecting the effect due to compressive forces in tectonic zones. The latter can cause very large errors in the pressure estimates. Estimation of the concentration factor in endogenic processes is only rarely possible mainly because we do not generally know the form in which the constituent migrated. For instance the particular element in question may have migrated as a diffusing ion, in a gaseous form, or as some soluble species such as a sulphide complex, carbonate complex, etc. For each of these forms the concentration factor in the chemical potential is different. In addition the form of migration may change, being a diffusive ion at great depths and a simple or complex soluble species as the element on its upward migration enters near-surface fractures filled with water. All of these imponderables make any estimation of the chemical potential of a constituent virtually impossible at our state of knowledge. If metamorphic or granitization processes are responsible for the formation of epigenetic gold deposits as many now suppose, there are yet other energy factors for consideration. One of these, the most important, is the energy required to mobilize an element or its compounds from a bound state in the rocks. If the element or its compounds are mobilized from the lattices of minerals, much more energy is generally required than that for mobilization of the same element or its compounds from grain boundaries. In addition it is also axiomatic that each of the elements and their compounds have specific mobilization energies from their bound states.

To summarize briefly we see that the mobilization of an element or its compounds from rocks, its migration and its precipitation in a new site such as a fracture is a most complicated process in an energy context. Not only differential mobilization energies prevail for the different elements, but a whole array of factors affect the chemical potentials. We cannot yet put numbers on the mobilization energies nor on the chemical potentials in endogenic processes. Until we can we shall not understand mineral zonation and paragenesis in a quantitative sense.

Nevertheless, it is possible to assign a qualitative index to the migration capacity of an element from our knowledge of its geochemistry. Thus, certain elements possess high migration energies, whereas others have low migration energies. The former migrate reluctantly under conditions of ore formation, or stated another way they require a large amount of thermal, solution or other energy to maintain them in a mobile state. They have low migration capacity indexes. Other elements migrate readily and have high migration capacity indexes, and elements with all grades of intermediate migration capacity lie between these extremes. An example of an element (compound) that has a high migration capacity index is silicon (silica). It is found in practically all mineral deposits from the highest temperature to the lowest and occurs in deposits in all grades of metamorphism. An element with a low migration capacity index is titanium, its minerals being generally concentrated only under relatively high temperature conditions. Zirconium has a similar tendency. It should be noted, however, that these general tendencies are not rigid; there are for instance situations where zirconium, as a complex, is relatively mobile in carbonated waters.

Based on their thermodynamic properties, diffusivity, binding energies in lattices, ability to form soluble complexes, solution properties under different Eh/pH conditions and ability to form colloids one can arrange the common elements in groups having migration capacities as follows:

Gangue elements:

$\mathrm{Si > B > K > Na > Ca = Mn > Mg > Co > Fe = Ni > Al}$

Gaseous compounds:

$\mathrm{CO_2 = S = Se > As > Sb > Te}$

Base metals:

$\mathrm{Hg > Zn > Cd > Cu > Pb > Mo = Bi = Sn = W}$

Precious metals:

$\mathrm{Ag > Au > Pt}$

This sequence is somewhat similar to that proposed by Udodov and Shvartsev (1965) for the coefficients of migration of certain trace elements in natural subsurface waters. These authors do not include silicon or the various gaseous elements in their table, but they indicate that gold has the highest coefficient of migration, i.e., the metal is the most mobile of the elements considered.

The migration capacity index of gold (and silver) in epigenetic processes is essentially the same as silicon (silica) as judged by the universal occurrence of both precious metals with quartz. Similarly gold has about the same migration capacity index as sulphur, arsenic and antimony. With respect to the base metals it would seem to fall between mercury and zinc. The reason for the relatively high migration capacity of gold during endogenic processes would seem to be partly due to the fact that in rocks gold is not usually in isomorphic replacement sites in mineral lattices, but rather the metal is present in microfractures and other discontinuities in minerals and rocks from which it is readily mobilized. That this is so is proven by the fact that gold is relatively easily leached from rocks and minerals as Davletov *et al.* (1973) have shown. This feature is also indicated by the long known fact that practically every quartz vein and stringer in zones of medium to high grade metamorphism contain small but detectable amounts of gold. There is also a considerable array of experimental data (*see* the section on gold in natural waters in Chapter II), which shows that gold is a highly mobile element under a great variety of chemical conditions.

The high migration capacity of gold has interesting consequences in the reworking, recrystallization or metamorphism of epigenetic deposits following the initial deposition of gold with early formed pyrite and arsenopyrite. The problem of the various generations of gold in deposits was analyzed by the writer many years ago (Boyle, 1961*a*). Briefly, the situation at Yellowknife, as well as in many other gold deposits in Precambrian greenstone belts, is that there are at least two ages of gold. At Yellowknife there are some four ages of gold and silver. These are as follows, the oldest first:

1. Early gold and silver contained in pyrite and arsenopyrite in the alteration zones and in quartz lenses. Much of this gold and silver is present in pyrite and arsenopyrite in lattice sites or in an extremely finely divided submicroscopic form. To free these two elements, roasting followed by cyanidation is commonly necessary.

2. Native gold containing silver; gold and silver in solid solution in sulphosalts in fractures and crushed zones in the quartz lenses and their alteration zones. Four types of native gold are present. One variety possesses a light yellow colour and is generally rich in silver. A more abundant type has a rich golden colour and occurs as blebs, sprigs and irregular masses in fractures in quartz and in granulated pyrite and arsenopyrite; also in sulphosalts, stibnite, chalcopyrite, etc. It is often accompanied by aurostibite. A third variety, of limited occurrence, is a reddish coloured gold that is often associated with chalcopyrite. The fourth variety occurs on slickensided surfaces of chlorite and sericite schist as thin films and gives the appearance of being painted on the surfaces.

3. Native gold containing silver; gold and silver in solid solution in freibergite, bournonite and other sulphosalts, and chalcopyrite. The native gold occurs in calcite and ankerite filling vugs and crushed parts in crosscutting quartz-carbonate veinlets. It is generally accompanied by the sulphides and sulphosalts mentioned above.

4. Native gold containing silver in late fractures cutting the orebodies. This gold is generally associated with pyrite and scalenohedral calcite and occurs as splendent leaf gold, spongiform gold and distorted octahedral crystals. In one case in the Giant System the leaf and sponge gold were observed in an ice lens (Boyle, 1951).

The presence of successive ages of gold and silver is usually explained by separate introductions from magmatic solutions. Just why this should take place has, however, not been satisfactorily answered. It would seem that a more plausible hypothesis, having regard to the geochemical facts at our disposal, is that the succeeding ages of gold and silver are simply due to the redistribution of the two elements orginally in the first generation of sulphides. The process would probably be as follows: gold and silver together with other chalcophile elements, sulphur, arsenic and antimony, migrated into and through the schist of the shear zones. When they found a site of marked dilatancy, early high-temperature pyrite and arsenopyrite were formed, which incorporated the available gold and silver in their lattices. As the deposit cooled and successive structural adjustments took place with crushing and partial recrystallization of the early sulphides, some gold and silver were exsolved together with some sulphur, antimony and other chalcophile elements. These migrated into nearby fractures where the secondary sulphides were precipitated together with native gold. At this stage aurostibite ($AuSb_2$) was probably formed by reaction of gold and antimony, and much gold and silver were incorporated in the various sulphosalts which formed at this time. The third age of gold and silver in the crosscutting quartz-carbonate veins probably had a similar origin. The fourth age of gold may owe its origin in part to supergene processes and was precipitated from underground waters in late fractures and faults.

Others have noted the phenomenon of remobilization of gold after its initial deposition in deposits. Bichan (1947) comments on the fact that gold has rarely remained at the original point of precipitation and thinks that the distinctive concentration of the metal into shoots, separated by zones of relatively barren vein material, is the result of lateral or vertical migration of gold from zones of extreme pressure or compression into nearby zones of tensional dilation. Moiseenko (1965) and Moiseenko *et al.* (1971) in studies of the gold deposits of the Pacific Belt, U.S.S.R. and particularly of the metamorphism of the Priamur gold deposits, noted that the fineness of gold increased and the form and internal structure of the native metal were changed from that initially deposited. Experimentally they noted that when gold-bearing ores were heated the small gold particles recrystallized and formed larger aggregates of greater fineness than the original particles. During the heating Au is more inert than Hg, As, Sb, Zn and Ag; the latter elements partly migrated out of the gold particles. At 700°C in the system Au-Ag the rate of diffusion of Ag was found to be 2.5 times greater than that for Au. Numerous details on the diffusivity of gold are given in the second paper. Petrovskaya (1970) noted redeposition of both quartz and gold during plastic deformation of early quartz veins of the Yenisei Ridge, U.S.S.R. And finally, Sakharova *et al.* (1972) heated polished specimens of auriferous minerals including pyrite, pyrrhotite, chalcopyrite and arsenopyrite from the Darasun deposit, U.S.S.R. This deposit is noted for its invisible and microscopic gold in the sulphides. During the heating tests some of the fine dispersed gold grew into larger particles, and some was completely dispersed. The migration of the gold began in the range 250 to 300°C. The investigators concluded from their experiments that initially deposited gold may undergo redistribution over a long time interval down to temperatures as low as 150°C.

It should be emphasized that not all auriferous deposits have multiple ages of gold due to the reworking or the regeneration processes described above. In many deposits it is evident that the different generations of gold are due to separate introductions of the metal during the mineralization process, each generation being keyed to dilation (fracturing) of the deposits. Some of the deposits in sediments (saddle reefs) and many of those formed under near surface conditions during the Tertiary appear to fall into this category.

Finally, if we accept the migration capacity index concept during endogenic mineralization it is relatively easy to construct a model of the regional zonation and many other features of the separation of elements during the mineralization history of a simple area. Thus, near granites or granitization centres only those elements such as tin and tungsten with low migration capacities (high mobilization energies) can be mobilized in the enclosing host rocks and concentrated in available dilatant structures. Elements with high migration capacities (low migration energies) will be set in motion in these environments, but they cannot be precipitated; hence, they will migrate into cooler zones where they are subsequently precipitated in available dilatant structural sites or chemical traps. Similarly those elements with low migration capacity indexes are precipitated first in the paragenetic sequence, followed successively by those with increasingly higher migration capacity indexes.

Where the situation is complex with a number of pulsations or epochs of mineralization the model is necessarily more involved. The situation in the Keno Hill area of Yukon, Canada will serve as an example (Boyle, 1965*a*). There, the country rocks are mainly folded and faulted phyllites, schists and quartzites, and the first phase of mineralization is marked by early barren quartz veins and boudins; the second by scheelite-bearing skarn bodies, a cassiterite replacement lode, and small pegmatites and coarse-grained quartz veins and lenses carrying scheelite and wolframite; the third by quartz-pyrite-arsenopyrite-sulphosalt-gold veins in extensive faults; and the last by one or more generations of siderite-quartz-galena-sphalerite-freibergite veins in extensive faults. All stages are clearly marked in time being punctuated by tectonic events resulting in a variety of suitable dilatant zones. Gold only appears in the third stage; the last stage is phenomenally rich in silver. With respect to thermal centres manifested in the area by intrusive granitic bodies the following zonation is evident. The first stage quartz bodies occur throughout the area and show no zoning relationship to the intrusives; the tin-tungsten bodies are localized in or near the granitic stocks; the quartz-pyrite-arsenopyrite-sulphosalt-gold veins are widespread but mainly without the intrusives; and the siderite-galena-sphalerite-freibergite lodes lie well outside the intrusives, generally midway between two major granitic stocks.

The mode of formation of these various ages of deposits at Keno Hill has been explained by the writer as follows: During the initial period of folding and regional low-grade metamorphism numerous small dilatant zones were formed in the country rocks, and these were filled with the more mobile constituents in the country rocks (e.g., those elements and compounds with high migration capacity indexes, mainly SiO_2, CO_2, Ca, etc.) to form the myriad stringers and lenses of quartz containing a few carbonates in places. During the main period of regional metamorphism and granitic intrusion, water and carbon dioxide were mobilized as a result of the rise of the geotherms through the sedimentary pile. Mobilization of SiO_2, S, As, Sb, Zn, Pb, Ag, Au, etc., was thereby facilitated, but little migration of any of these constituents, including H_2O and CO_2, took place until the vein faults were formed. Once this occurred the more mobile constituents, viz., SiO_2 and some S, As, Sb, Fe and Au, were drawn into the vein faults and precipitated in the more dilatant parts to form the quartz-pyrite-arsenopyrite-gold lodes. Following this period of mineralization, increased temperatures at depth coupled with renewed tectonic activity and the formation of more extensive dilatant zones brought larger quantities of CO_2 and S into the diffusion system. The CO_2 strongly depressed the mobility of silica, as mentioned in a previous section in Chapter II, but at the same time this constituent, together with sulphur, greatly enhanced the mobility of Fe, Mn, Mg and the chalcophile elements, Zn, Pb, Ag, etc. All these constituents were drawn into the extensive dilatant parts of the vein faults to form the siderite-galena-sphalerite-freibergite lodes.

The formation of the various types of deposits through a long time interval has depended, therefore, on the timing of regional metamorphism, granitic intrusion and tectonic activity and ultimately on the migration capacity index of the various elements involved in ore formation.

General synthesis of the metamorphic secretion-dilation theory of the formation of epigenetic auriferous deposits

The generalized mechanisms implicit in the metamorphic secretion-dilation theory of the formation of auriferous deposits have been outlined in the various sections above. It now remains only to summarize these mechanisms and amplify them with a few details.

Three principal types of epigenetic auriferous deposits are known – deposits in skarn, deposits in fractures and faults exhibiting little if any wall-rock alteration and deposits marked by extensive alteration zones. The first is readily explained on the 'chemical trap' principle. As diffusing ions (or solutions) of the metals, set in motion from the country rocks by granitization or by the introduction of granitic bodies, migrate outwards from the thermal centres and reach chemically contrasting rocks such as limestones or calcareous shales reactions occur that result in the precipitation of silica, sulphides and the metals. Later dilatant structures developed in the skarns may draw in further increments of the migrating elements from the country rocks or from extensive skarnified rocks, thus forming local enriched shoots. This is the only part played by dilatancy in the formation of skarn orebodies.

Deposits, mainly auriferous quartz bodies without extensive alteration zones, formed in fractures or in openings on the crests of folds (saddle reefs) are due mainly to the effects of dilation of the structures. Thus, during the metamorphism and granitization of shale-greywacke sequences, silica, the metals, sulphur, arsenic and antimony are mobilized and migrate essentially by diffusion into available dilatant zones where the

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various elements are partitioned into the minerals we now find in the deposits. Silica, being one of the most mobile of the constituents, and being amply available in the shale and greywacke rocks, fills most of the dilatant zones as quartz, which generally contains some gold.

Where alteration is marked the chemistry of the formation of gold deposits is more complex. In Precambrian and younger volcanic belts where the gold-quartz deposits are often associated with great linear carbonated zones and have well-marked alteration zones the origin of the deposits can best be illustrated by a short historical synthesis as shown in Figures 91 and 96.

Following extensive outpouring of marine lavas and intermittent sedimentation most of the belts were folded, metamorphosed and partly granitized. During these orogenic processes, marked temperature gradients existed outward from the foci of granitization leading to the formation of the zone facies of metamorphism in greenstone belts and their associated sedimentary rocks. At this time much water, carbon dioxide, sulphur and probably some of the chalcophile elements were mobilized and migrated toward the cooler parts, that is, down the temperature gradient at right angles to the isothermal lines as shown by the vectors in Figure 91*a*. If there had been no structural breaks in the rocks the result would have been a simple metamorphic halo about a granitized centre.

However, in many greenstone belts a great system of shear zones was formed near the end of the orogeny and formation of the granitic bodies. As a consequence the migration vectors were radically changed by the dilatancy of the shear zones as shown by Figure 91*b*. The shear zones literally sucked the mobile carbon dioxide, water, sulphur and other elements from the country rocks and channelled them toward the surface. Because of the great extent and depth of the shear zones the effects of dilatancy were undoubtedly felt over great volumes of the country rocks, and mobile elements were probably contributed from points thousands of feet horizontally and vertically from the shear-zone systems. Extensive structures, which impose such marked dilatant effects on the country rocks, may be termed 'first-degree' dilatant zones (Fig. 96).

During the formation of the large shear zones, carbon dioxide, water and sulphur reached a high concentration along them. As a consequence the chemical equilibrium was strongly displaced, and chloritization, carbonatization, pyritization, etc. of enormous tonnages of volcanic rock took place. This led to the liberation of silica, potassium, calcium, iron, etc. in addition to gold, silver and other metallic elements present in the rock affected by alteration. These liberated compounds and elements, together with those added to the shear zones by diffusion from the country rocks, migrated laterally and vertically to 'second-degree' low-pressure dilatant zones at shear-zone junctions and other structural locales where contorted zones or openings were formed. In these sites, secondary reactions promoted by the low-pressure and lower-chemical potential, resulted in the precipitation of quartz, carbonates and gold- and silver-bearing pyrite and arsenopyrite, forming quartz-sulphide lenses with adjacent alteration haloes. The details of the formation of auriferous quartz lenses and veins in the second degree dilatant zones (Fig. 96) are complex but are of great importance and merit some description.

As noted above, the shear-zones when first formed constituted first-degree dilatant zones into which the volatiles were drawn from the surrounding rocks. Once in the structures

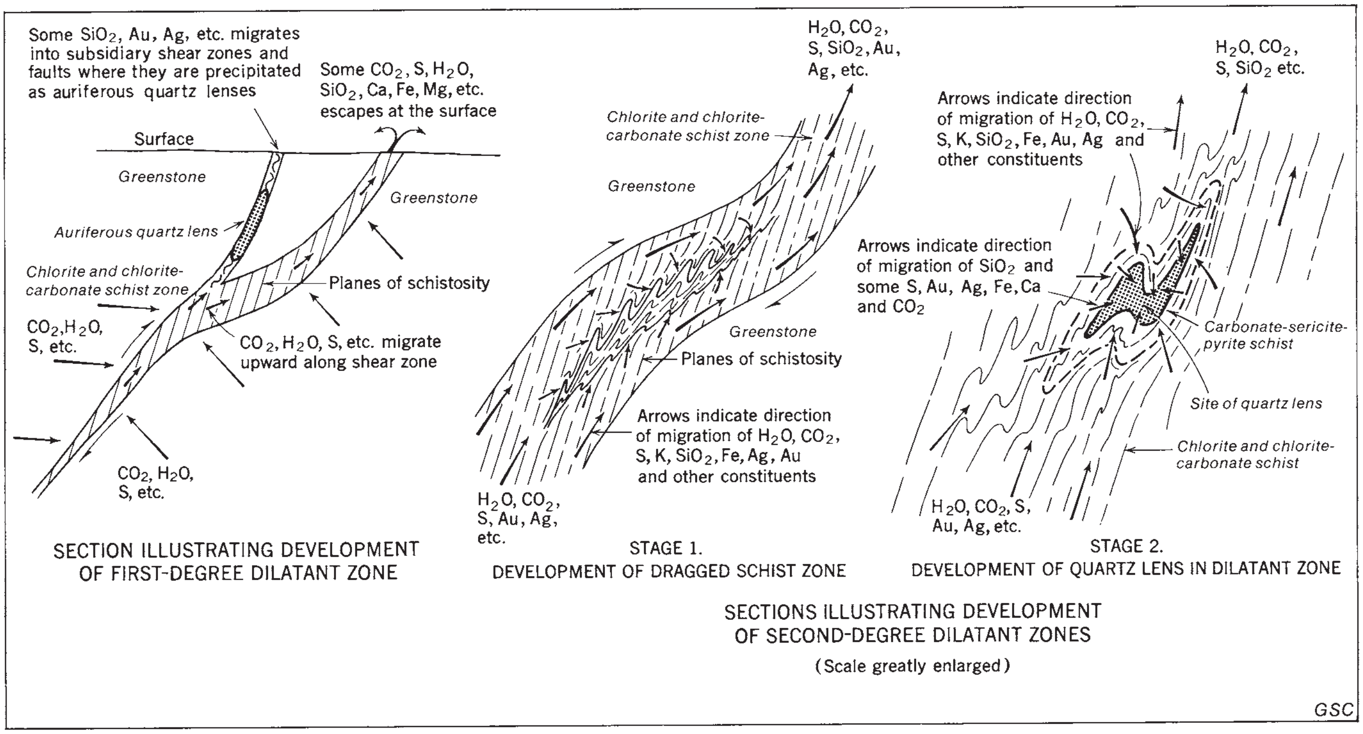

Figure 96. Diagrams illustrating development of first- and second-degree dilatant zones, alteration zones and auriferous quartz lenses.

the volatiles would tend to migrate upward toward the surface that would be the region of lowest pressure, and hence there would be a constant flux of volatiles migrating through the shear zones toward the surface. During this process, the chemical equilibrium was severely displaced, and carbonization and hydration of the silicates took place transforming enormous volumes of rock and releasing large amounts of silica as well as much gold, silver and base metals. The gold together with the silver, base metals, sulphur and arsenic migrated upward and may have been partly dispersed at the surface. This interaction of both chemical and structural factors produced the extensive chlorite and chlorite-carbonate schist zones containing only scattered small quartz lenses. The great linear carbonated zones in many greenstone belts are manifestations of this process. These are frequently either low in gold or leached of some of their gold and other elements. The writer estimates that in some of these carbonated zones at least half of the gold in the rock has been mobilized and moved either into the second-degree dilatant zones noted below or into fractures and faults that are subsidiary to the great carbonated zones.

During the course of the formation of some of the first-degree shear zones as outlined above, particular parts were subjected to intense contortion and dragging at structural sites such as shear zone junctions and flexures. These severely contorted sites marked second-degree dilatant zones further disturbing the chemical equilibrium within the shear zones. The migrating volatiles together with released potash and silica from the chlorite zones streamed toward these sites where the following reactions took place.

(Ca,Mg,Fe silicates) + CO_2 = ankerite + silica
(Ca,Mg,Fe silicates) + S = pyrite + silica + Ca + Mg + other constituents
(Ca,Mg,Fe silicates) + S + As = arsenopyrite + silica + Ca + Mg + other constituents
Chlorite + K^+ = sericite + other constituents

As the volatiles were delivered to the contorted sites, dilatancy (volume increase) must have proceeded concomitantly, otherwise the reactions would not have run from left to right, because one of the principal products, silica, must be withdrawn. Once dilatancy ceased the reactions stopped, and equilibrium was restored. The net result, therefore, was the formation of quartz lenses in the more dilatant parts surrounded by desilicated carbonate-sericite-pyrite-arsenopyrite zones grading into desilicated chlorite-carbonate zones.

The formation of the quartz lenses and their alteration zones, as suggested above, is actually the operation of Reicke's principle on a grand scale whereby various mobile constituents are transferred from zones of directed high pressure to those of low pressures. The thermodynamics of the process are complex and not given to a simple exposition here. It is sufficient to state simply that the mineralogical changes in the shear zones merely reflect the chemical adjustments attendant upon the chemical potential differences induced by dilatancy. The transfer of the various constituents was essentially down the pressure gradient, and the migration vectors have in general been oriented toward the low-pressure zones.

The state in which the mobile constituents were transferred through the shear zones can only be inferred from our present inadequate knowledge of the physical chemistry of diffusion of matter in solids. It is probable that most of the constituents were transferred in a gaseous or ionized state because many of the constituents such as water, carbon dioxide, sulphur and arsenic pass readily into the gaseous state. Furthermore it is well known that gases at high temperatures and pressures diffuse more readily through solids than do liquids. Another important consideration is that silica and other oxides have a marked solubility in gaseous water at high temperatures as shown by numerous investigations.

Water was undoubtedly the main catalyst in the processes whereby numerous constituents were transferred through both the country rocks and shear zones. Under the deep-seated conditions of formation of many of the gold-quartz lenses in greenstone belts the state of the water was probably gaseous, as noted above, and it may have been partly ionized as H^+, H_3O^+ and OH^-. Carbon dioxide probably existed as the ionized components of carbonic acid, H^+, HCO_3^- and CO_3^{2-}, and sulphur was probably present as H_2S or the ionized components of this gas, H^+ and HS^-. Silica was probably hydrated as $Si(OH)_4 \cdot nH_2O$ but may also have migrated as hydrated sodium and potassium complexes. Numerous other constituents were probably transferred as hydrated complexes.

There seems to be little justification for assuming that the migration of the constituents through the shear zones required the movement of large volumes of water. Ions, especially when hydrated, diffuse readily through gaseous water at high temperatures. This mechanism, therefore, provides an adequate means of transport, and in the writer's opinion the migration of the elements took place through a nearly stationary flux of gaseous water that permeated both the country rocks and shear zones. The density of the hydrous flux was probably controlled in part by the thermal gradient and also by the dilatancy of the structures. Such a mechanism of transport is actually analogous to the diffusion of ions in liquid water, a phenomenon well known to chemists and shown to be applicable to mineralization processes many years ago by Duffell (1937).

The relative rates of migration of the various constituents through shear and schist zones is a problem that requires much experimental data for an adequate solution. The main factors bearing on the problem can, however, be stated and an attempt can be made at interpreting some of the chemical features of the shear and schist zones.

Shearing was undoubtedly one of the most important factors. It is well known that shearing strains mineral lattices and promotes diffusion (Mott, 1955). In addition, extreme contortion also comminutes the minerals increasing chemical reaction. Furthermore, the effects of directed pressure, such as shearing, on the mobility of the elements, must also be considered. Bridgman (1931) has shown that all atoms can be compressed at high pressures, and that the compressibilities of the alkali metals are greater than those of other elements. It can also be shown from lattice theory that the greater the compressibility of an element the weaker is its bonding energy. It follows, therefore, that under great shearing stress, the more compressible an element the easier it will be detached from its lattice. As Bugge (1945) has suggested, this phenomena is a plausible explanation for the relatively high mobility of the alkalis compared with calcium, magnesium, etc., in zones of intense shearing. In the shear zones, excepting the volatiles, soda and potash commonly exhibit the largest percentage gains and losses, attesting to their higher mobility compared with other constituents. (*See for example* Tables 46, 47 and 48.) This higher mobility can probably be attributed in part to the action of shearing in view of the theoretical concepts mentioned above.

When water is present in the system, consideration must also be given to the effect of the ionic potential[30] on the migration of the elements. Elements such as potassium, sodium, calcium and magnesium have a relatively low ionic potential and form easily soluble cations that are not readily precipitated by changes in pH. Elements like iron and aluminum have an intermediate ionic potential, are readily hydrolyzed, and their solubilities are largely pH dependent. Silicon, sulphur, phosphorus, etc., with high electrostatic charges and high ionic potentials, form oxy-acid anions whose solubilities may depend in part on the pH of the environment.

As noted above, sodium and potassium have low ionic potentials, and their cations are readily soluble. Transfer of these elements through a pervasive water gas would, therefore, be relatively easy and hence their mobility in the shear zones was high. Calcium and magnesium, on the other hand, have higher ionic potentials and their mobility was lower as shown rather conclusively by their smaller percentage gains and losses in many shear zones as compared to sodium and potassium (Tables 46, 47 and 48).

Silica forms complex ions whose solubilities vary only slightly with pH near the neutral point; at high and low pH's their solubilities increase. Referring to the tables just mentioned one sees that the percentage gains and losses for silica in many shear zones are not high suggesting that the pH of the environment was close to the neutral point. For alumina the percentage gains and losses are relatively low indicating a low mobility for this constituent. Aluminum is an amphoteric element with a relatively high ionic potential, and alumina has solubility maxima at pH 4 and 10. The iron oxides show intermediate values in their percentage gains and losses indicating a moderate mobility. This means that the pH of the environment during the migration of iron must have been on the acid side because the mobility of iron above pH 7 is relatively low. Correlating these observations on silica, alumina and iron, it seems logical to conclude that a slightly acidic to neutral condition prevailed during the main stages of the alteration processes.

The effects of carbon dioxide, sulphur and arsenic have not been considered. Their presence has without question modified the course of the reactions and the mobility of many elements. It would be expected that carbon dioxide would have increased the acidity and hence promoted the migration of Ca, Fe, Mg and Mn and perhaps K and Na. The presence of sulphur and arsenic, especially in a gaseous hydrated form, would certainly have promoted the migration of many of the trace elements such as Cu, Zn, Au, Ag, etc. As the volatile constituents were used up, the pH of the environment probably became alkaline permitting a greater migration of silica and perhaps alumina.

It is apparent, therefore, that the mobility and transfer of the elements in shear zones in greenstone belts has depended upon several interacting factors. Chief among these was shearing which comminuted the rock, permitting extensive chemical reaction to proceed. It also promoted diffusion, and because of the intrinsic feature of compressibility certain elements such as Na and K were more readily detached from their constituent minerals than others. Once free the elements migrated in accordance with their ionic potentials. Those with low ionic potentials migrated freely; those with high potentials less so. The pH of the environment was critical for the migration of some elements especially aluminum and iron. The influence of carbon dioxide, sulphur and arsenic was marked not only in promoting the migration of Ca, Mg, Fe, etc., but also the metallic trace elements and finally in fixing many of the elements in the carbonate and sulphide minerals of the shear zones. The schist of the shear zones and the early quartz lenses were thus formed essentially contemporaneously as the result of intense shearing, which triggered and promoted the chemical effects characteristic of many of the auriferous deposits in greenstone belts.

During cooling of the deposits and further structural adjustments within the shear zones, much gold, silver, antimony and other elements were exsolved from the early sulphides and found their way into local dilatant zones such as fractures in quartz lenses and local tension fractures and small faults in the shear zones. Some silica and the components of the late carbonates did likewise. This process gave rise to the successive later generations of native gold, sulphosalts, pyrite, quartz and carbonates in the shear zones of most greenstone belts.

In deposits of all ages the sequence of events and the details of the geochemistry of the formation of the auriferous deposits were probably much the same as those described above. Certain deposits in rocks overlying basement complexes, such as many of those of Tertiary age as well as some of those of older vintage, may have had a slightly different history. Many of these deposits seem to have derived some or all of their constituents from the rocks of the basement complexes, particularly from pyritiferous graphitic shales, greywacke and quartzites that underlie many of the auriferous belts. The mechanism of concentration of the quartz, the gold and silver, and the various other gangue and base metal minerals differs only in detail from what has been described above. In some cases the quartz, and indeed some of the gold and other metals, may have originated mainly from the pervasive propylitization of andesites and other rocks. In other cases the thermal wave associated with deep-seated volcanism probably mobilized the vein constituents in the basement rocks, and these were drawn into the extensive dilatant fractures and faults formed in the superincumbent andesites, breccias, dacites, etc. A schematic representation of the probable process has already been illustrated in Figure 92.

In passing it is interesting to note that only certain Tertiary volcanic districts are auriferous despite the fact that basic to acidic volcanics are present and the basement rocks are favourable sediments and/or volcanics. One can contrast the auriferous Tertiary volcanics of Romania and New Zealand and the barren volcanics of Scotland and eastern Australia in this respect. In my experience the difference between productive and nonproductive auriferous Tertiary volcanic

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[30] The ionic potential is the charge of an ion divided by its radius and is a measure of the behaviour of an ion towards water.

districts lies in the phenomenon of propylitization. In Romania, New Zealand and in other productive Tertiary auriferous belts propylitization is extensive; in Scotland, Ireland, eastern Australia and elsewhere the Tertiary rocks are relatively fresh, and there are no gold deposits despite the fact that the strata are commonly highly faulted. Whatever has produced the extensive propylitization has also produced the gold deposits. More research on this phenomena, why it is present in some areas and absent in others, is obviously needed.

Origin of the auriferous and uraniferous quartz-pebble conglomerates

These deposits, the largest gold producers in the world, have had a controversial history as regards their origin since they were first discovered in the last part of the 19th century. As noted in the section describing the deposits in detail, two principal ideas have been suggested for their origin – a placer or modified placer origin for the gold and uranium, and a hydrothermal origin for the two metals. The pros and cons regarding each hypothesis are discussed in detail under the description of each deposit or group of deposits and need not be repeated. In the following the writer will briefly review some of the salient geological and geochemical characteristics of these deposits and inject his own thoughts into a final synthesis of how he thinks the auriferous and uraniferous quartz-pebble conglomerates originated.

The rocks in which the deposits occur are clastic sediments, principally conglomerates and quartzites, laid down in great subsiding basins on basement rocks of varied types. The stratigraphic sequence in some basins contains volcanics, mainly the basic variety. Conglomerates and quartzites in basins overlying terranes marked by the presence of auriferous deposits in greenstone and associated sedimentary belts that are invaded by granitic rocks are generally gold bearing (Rand, Tarkwa) and some are also uraniferous (Rand). Those overlying terranes marked mainly by granitic rocks and gneisses are not generally auriferous but are commonly enriched in uranium, thorium and rare-earths (Blind River–Elliot Lake). From these observations we can conclude that the provenance of the sedimentary materials is an important parameter in assigning a source to the gold, uranium, rare-earths, etc.

The broad geologic setting of the various basins is of interest. Considering the Rand and the Blind River–Elliot Lake deposits it seems probable that both lie in basins flanked by extensive faults that probably mark great graben structures. Volcanism is evident in both basins, although the volcanics are not present in the immediate Blind River–Elliot Lake area. Great basic intrusives are present somewhat removed from the basins (Bushveld complex and Sudbury eruptive), but within the general geological framework. In the Rand, dykes of Bushveld age intrude the rocks of the basin, and in the Blind River–Elliot Lake basin dykes of Sudbury eruptive age, likewise, intrude the basin. And finally, there is a distinctive type of mineralization related in some manner or other to these basic intrusives, which in both South Africa and Canada includes gold veins, copper deposits of several types and nickel-cobalt-platinoid mineralization. Broadly speaking these features are also evident in the vicinity of the Tarkwa and Jacobina basins, although the late stage of mineralization associated with the basic bodies is weak or absent. How these various features are to be integrated metallogenetically cannot at present be deciphered, but they should be kept in mind by future researchers dealing with the origin of these deposits. It is of interest to note the similarity in the setting of the auriferous conglomerates and the copper conglomerates and quartzites in the Keweenaw Peninsula, Michigan. Jolly (1974) suggested that the copper in the conglomerates was derived by metamorphism (dehydration) of underlying volcanics rather than derivation of the copper by magmatic hydrothermal solutions as is generally supposed. In other words the copper was redistributed within the sedimentary-volcanic pile as a result of diagenesis and metamorphism – exactly the same process that has been suggested by many for the postplacer history of the gold in the Rand and other similar deposits.

The mineral composition of the quartz-pebble conglomerate deposits is variable. The principal iron minerals are pyrite and iron oxides, both being apparently mutually exclusive in individual deposits. Deposits that contain abundant pyrite are generally uraniferous, whereas those that contain only the iron oxides do not seem to be uraniferous. The occurrence of gold is independent of the presence of pyrite or iron oxides, the precious metal occurring in both types of deposits (Rand, Tarkwa) in economic amounts.

Some of the pyrite in the quartz-pebble conglomerates is detrital, but the largest amount is authigenic. The iron oxides in the deposits appear to be partly detrital and partly authigenic. The sulphur in the pyrite of the various deposits, so far as is now known, does not show the marked fractionation effects usually attributed to biogenic (bacterial) activity, although some of the authigenic pyrite in the Rand exhibits a slight shift towards enrichment in ^{32}S that may be due to bacterial transformations.

Deposits that contain abundant pyrite generally also have small amounts of a number of other base metal sulphides, particularly pyrrhotite, sphalerite, chalcopyrite and galena. Nearly all of these sulphides are authigenic minerals. It is of interest to note that many conglomerates and quartzites at or near unconformities are frequently enriched in authigenic base metal sulphides; few of these are even slightly auriferous, uraniferous or thoriferous. Here, we may mention the Laisvall deposits in Sweden; the Maubach deposits near Aachen, West Germany; the Silver Mine deposits near Sydney, Nova Scotia; and the disseminated base metal mineralization in the Cobalt quartzites at Cobalt, Ontario. The source of the constituents in the base metal sulphides in these deposits, as in the pyritiferous auriferous quartz-pebble conglomerates, is uncertain.

The gold in the auriferous quartz-pebble conglomerates is invariably very fine grained (~ 0.05 mm) and has a definite authigenic appearance in all deposits. Nuggets of variable size such as occur in Tertiary and Quaternary placers do not occur in the quartz-pebble conglomerates. The fineness of the gold in most of the quartz-pebble conglomerates averages about 925, a relatively low fineness (high silver content) for placer deposits. The fineness is commonly uniform in the deposits, another feature that contrasts with modern placers. As Horwood (1917) pointed out many years ago, the purity of detrital gold is generally in inverse proportion to the size of the grains. Considering the size of the gold in the Rand and other similar deposits one would expect the gold to have a very high fineness if the metal was simply detrital in origin.

The radioactive minerals in the quartz-pebble conglomerates, including uraninite and brannerite, occur in discrete grains, in tiny veinlets and in thucholite as fine disseminations. Most of the radioactive minerals are probably authigenic in the writer's opinion; some may be detrital, but the amount is small. Even the detrital component appears to have been highly modified.

Thucholite and other types of carbonaceous substances are universally present in the Rand deposits but appear to occur only in small amounts in the other deposits. The mineraloid occurs in small globules 'fly speck carbon', in thin columnar seams, in small veinlets and as small isolated patches. The thucholite encloses minute particles of uraninite and small irregular sprigs and particles of gold. Some seams of thucholite in the Rand (Carbon Leader) are exceptionally rich in platinoid minerals, native silver, Ni-Co arsenides and various sulphides. Gold exhibits a particularly close association with the thucholite. Many suggestions have been ascribed for the origin of the thucholite. Some say it is a polymerized hydrocarbon and others that it represents the organic remains of algae, lichenlike plants and so on. The writer is of the opinion that nearly all of the thucholite and other similar solid hydrocarbons are polymerized residues of petroleumlike materials derived in some manner, as yet unknown, from the humification of algae, bacteria and other low forms of life. There is a strong suggestion that these petroleumlike substances are capable of transporting gold, uranium, thorium and various other metals probably in a chelated form. As they set (polymerize) in a gellike mass, hence the ovoid and columnar form of many of these hydrocarbons, the gold, uranium and other components are split out, appearing as minute inclusions or along cracks in the hardened gel. Some of the columnar varieties of thucholite in the Rand appear to be lichen mats as suggested by Hallbauer and van Warmelo (1974), but the ovoid nodules and specks containing gold and uraninite are exactly the same as the thucholite, also with gold and uraninite, in the Richardson skarn gold deposit at Eldorado, Ontario, described by Boyle and Steacy (1973). In the latter, ovoid fungal hyphae or plant debris are ruled out, although the constituents of the thucholite probably derived ultimately from primitive organic matter.

The trace element content of the quartz-pebble conglomerate deposits reflects the abundance of the various allogenic and authogenic minerals. Notable are the relatively high contents of arsenic and mercury in some of the deposits. The signficance of this is uncertain. Both elements are commonly enriched in pyritic sediments, and hence they may be syngenetic in the deposits. On the other hand these elements are characteristic of epigenetic (hydrothermal) gold deposits. The very low contents of tin and tungsten in the deposits are difficult to explain by any hypothesis. If the deposits were originally placers one would have thought that the heavy concentrates would be somewhat enriched in tin and tungsten minerals. Cassiterite is, however, not generally abundant in Precambrian (Archean) terranes, and this may be the reason for its paucity in deposits such as the Rand. Tungsten minerals, especially scheelite, are common in auriferous Precambrian deposits and being heavy and resistant should have collected together with gold in the placers. However, the amount of scheelite in Precambrian gold deposits is low, and dissipation throughout the vast volume of quartz-pebble conglomerates would probably have reduced the tungsten content below the detection limit by ordinary analysis. If one postulates a hydrothermal origin for the deposits, the absence of tungsten seems unusual considering that nearly all other types of Precambrian gold deposits contain detectable amounts of the element, and some are considerably enriched in scheelite. The content of zirconium in some of the reefs of the Rand and Elliot Lake (Table 35) seems low for most placers (average about 100 ppm), but this may be a feature of the provenance of the resistate zirconium minerals, mainly zircon. The presence of platinoids in the Rand is of interest. It is said that some of these elements (e.g., Pt, Pd, Ir, Os) are detrital, but those in the Carbon Leader cannot be detrital in the form in which they now occur. In this reef they are present as sperrylite, braggite, cooperite, and the metallic compounds platiniridium, platinum and osmiridium, associated with pyrrhotite, chalcopyrite and a variety of Ni-Co arsenides and sulphides. Such a mineralization suggests some connection with basic and ultrabasic rocks not necessarily as a result of magmatic differentiation processes but more probably related to metamorphic secretion from basic dykes or volcanics (Ventersdorp system and/or Bushveld intrusives). Whatever the origin of this mineralization, it should be kept in mind in future research.

The source and chemical history of the principal constituents of the matrix of the quartz-pebble conglomerates are of interest in the matter of the origin of these deposits. Microscopic examination suggests that the quartz in the matrix is probably only partly detrital, a considerable amount of silica having probably been initially present in a dissolved or colloidal state in the waters in which the conglomerates and quartzites were laid down. The same is probably true of the other components, particularly alumina, that now constitute sericite, chlorite, chloritoid, pyrophyllite and the other micaceous minerals. In addition to the hydrolysates, silica and alumina, it seems highly probable that a number of other hydrolysate elements followed these two main constituents of the matrix; here may be mentioned especially the rare-earths, thoria, zirconia, urania and titania, although the last (as rutile, leucoxene, etc.) may have been partly derived as residues of the sulphidization of black sand (ilmenite) if such a process went on during diagenesis and metamorphism. It seems probable that iron was delivered to the basins probably as ferrous sulphate, $FeSO_4$. Oxidation and hydrolysis within the sedimentary basin ultimately precipitated the iron as the hydrous and anhydrous oxides. The sulphate released was then available for transformation by bacteria to H_2S, which in most basins fixed much of the hydrous iron oxides as pyrite during sedimentation and diagenetic processes. In some basins (Tarkwa) the iron was fixed as the oxide and remained as such probably because of the absence of bacterial activity. The various reactions to produce pyrite from the colloidal iron oxides (limonite) are complex and not readily set down in equation form. The hydrolysis reactions are probably as follows:

$$12FeSO_4 + 3O_2 + xH_2O \rightarrow 4Fe_2(SO_4)_3 + 2Fe_2O_3{\cdot}xH_2O$$
$$Fe_2(SO_4)_3 + 3H_2O + xH_2O \rightarrow Fe_2O_3{\cdot}xH_2O + 3H_2SO_4$$

Splitting out of water from the hydrous iron oxides yields a limonitic product FeO·OH.

$$Fe_2O_3 \cdot xH_2O \rightarrow 2FeO \cdot OH + yH_2O$$

Bacterial action involving the sulphate available from the hydrolysis reactions yields H_2S.

$$3H_2SO_4 \xrightarrow{\text{Bacteria}} 3H_2S + 6O_2$$

The H_2S reacts with the limonitic product to give iron sulphide, which evidently recrystallizes or polymerizes in a complicated manner to yield pyrite.

$$4\,FeO \cdot OH + 4H_2S \rightarrow 4\,FeS + 6H_2O + O_2$$

$$FeS + S \rightarrow FeS_2$$

All of these reactions are apparently concomitant during sedimentation and diagenesis. In fact bacterial H_2S may act directly on any available $FeSO_4$ to produce iron sulphide directly and this recrystallizes or polymerizes to yield pyrite.

$$FeSO_4 + H_2S \rightarrow FeS + H_2SO_4$$

$$FeS + S \rightarrow FeS_2$$

It will be noted in the above discussion on iron that oxygen is required in the hydrolysis reaction. It has often been stated that the quartz-pebble conglomerates were accumulated under anoxogenic conditions. This seems improbable having regard to the presence of abundant iron-formations in older (Keewatin) and coeval rock sequences. In addition it appears probable that free oxygen was one of the elements entering the primitive oceans as a result of the early degassing of the earth (Boyle, 1976*a*). The presence of detrital pyrite in the quartz-pebble conglomerate and the possible presence of detrital uraninite in these rocks are not indications of the absence of oxygen in the atmosphere since abundant pyrite commonly occurs in placers in cold climates. It would seem that temperature is more significant than the presence of oxygen in the weathering of pyrite under certain conditions.

The foregoing preamble permits a synthesis of the possible origin of the auriferous and uraniferous quartz-pebble conglomerates and quartzites. These deposits are essentially sediments laid down in a subsiding basin, all of their constituents being either accumulated by detrital or chemical processes. The quartz pebbles and part of the quartz, sericite and other silicate matrix minerals are detrital, derived from the weathering of ancient granitic-greenstone terranes, some marked by the presence of auriferous deposits. Much of the silica and alumina in the matrix was probably delivered to the basin in solution or as colloids, as were also thoria, zirconia, the rare-earths, urania and much titania. Iron reached the basin most probably as dissolved ferrous sulphate or in some cases perhaps as colloidal hydrous oxides. Various hydrolysis reactions precipitated the silica and alumina as colloidal silica (quartz) and Al-Si complexes (clay minerals), and these coprecipitated and carried down most of the thoria, zirconia, the rare-earths, urania and titania as hydrous oxides or adsorbed constituents. The iron was precipitated as gelatinous hydrous oxides (limonite) as a result of hydrolysis, leaving the sulphate in a dissolved form in the interstitial waters of the sediments.

The form in which the gold reached the basin is problematical. It may have been delivered in solution or as a colloid. It seems more probable, however, that the gold was thoroughly milled and reached the basin as very fine flour or skim gold similar to that found in the sediments of many deltas. Whatever the form it appears that the gold was initially widely spread throughout the sediments, especially the conglomerates.

After the initial sedimentation processes a long interval of diagenesis prevailed followed by an extensive period of low-grade metamorphism. During diagenesis anaerobic sulphur reducing bacteria acting on interstitial sulphate-saturated waters produced much H_2S, and this reacted with available iron to give ferrous sulphide and ultimately pyrite or pyrrhotite. The residues of the bacteria gave rise to various oily substances that accumulated in the sediment. Where bacteria were absent the iron oxides recrystallized to give hematite as in the Tarkwa deposits. During the metamorphic period that followed considerable recrystallization, migration and formation of new minerals took place. The matrix of the conglomerates was recrystallized to yield sericite, pyrophyllite and secondary quartz. Ferrous sulphide gave rise to pyrite or pyrrhotite by polymerization and recrystallization processes, and there was considerable local migration of the constituents of the iron sulphides to give secondary or authigenic pyrite and pyrrhotite. At the same time constituents such as lead, zinc, arsenic, cobalt and nickel, originally incorporated in the initial ferrous sulphide complex, were split out and combined to give the various base metal sulphides, arsenides, etc. Under certain conditions as in the Rand, some of the gold and uranium were mobilized as metallo-organic complexes involving the hydrocarbon residues of bacteria and algae. These complexes then migrated and were precipitated in the more porous zones, particularly in the conglomerates, in the form of hydrocarbon gels from which native gold and uraninite were split out. Under other conditions much of the gold and uranium probably migrated in complex sulphide solutions from which pyrite, arsenopyrite, the base metal sulphides, uraninite and native gold were precipitated in favourable sites, mainly porous zones in the conglomerates and quartzites. During this stage of the redistribution of constituents in the sediments, but after penetration of the sediments by basic dykes and the deposition of basic flows in the Witwatersrand system, it seems probable that nickel, cobalt, the various platinoids and gold were mobilized from the sediments and especially from the basic dykes and flows and were precipitated in reducing environments particularly in the Carbon Leader (thucholite), which seems to have originated at least in part from organic (lichen) mats during sedimentation.

The last phase of the mineralization process in the auriferous and uraniferous quartz-pebble conglomerate deposits was the formation of quartz veins with sulphides and gold in fractures and small faults. These probably represent late secretion veins, their constituents being derived locally from the conglomerates and quartzites.

Thus, the formation of the auriferous and uraniferous quartz–pebble conglomerate deposits has involved processes of both a sedimentary and metamorphic nature. Constituents that were deposited both detritally and chemically were later mobilized during diagenesis and low grade metamorphism and concentrated after relatively local migration in favourable porous sites mainly in the conglomerates. The results of such processes can be seen today in an embryonic stage in certain older Mesozoic-Cenozoic fossil placers in the Urals (Barannikov *et al.*, *in* Petrovskaya, 1974) and in numerous young (Tertiary) placers in California, Australia and elsewhere.