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THE GEOCHEMISTRY OF GOLD AND ITS DEPOSITS (together with a chapter on geochemical prospecting for the element)

R. W. Boyle

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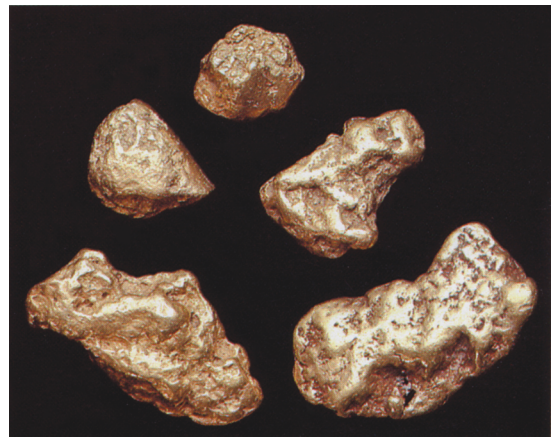
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Native gold, Paymaster mine, South Porcupine, Ontario (Natural size).

Native gold nuggets, Goldrun Creek placer, Cassiar District, British Columbia (Natural size).



The gold cups of Vaphio: From the tholos tomb near Vaphio, Laconia, Greece. First Late Minoan, late 16th-early 15th century B.C., National Archaeological Museum, Athens.



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This book is dedicated to all those
who have moiled for gold in the rain
and cold and under the tropic sun,
and have used their winnings wisely.

Preface

Gold, the noblest of metals, has been utilized by man for more than 5000 years, first in artistic objects and jewellery, then largely in coinage and more recently in the industrial arts. The metal is today the principal medium for settling international accounts. Despite the great commercial and artistic value of gold, little was actually known about the geochemistry of the element until the middle of the present century; since then considerable research in various geochemical aspects of the metal has been carried out.

The author here presents a comprehensive compilation of the geochemistry of gold, partly from his own research, which has extended over 25 years, and partly from the literature. He describes the principal types of gold deposits and discusses their origin. The data here presented, in addition to being a fundamental contribution to the geochemistry of gold, will be found useful to those interested in geochemical prospecting for the element.

D.J. McLaren
Director General
Geological Survey of Canada

Ottawa, 25 August 1976

THE GEOCHEMISTRY OF GOLD AND ITS DEPOSITS

Abstract

Gold is a member of Group IB of the periodic table, which includes copper, silver and gold. In its chemical reactions gold resembles silver in some respects, but its chemical character is markedly more noble. The principal oxidation states of gold are Au(I)(aurous) and Au(III)(auric). These states are unknown as aquo-ions in solution, the element being present mainly in complexes of the type $[\text{Au}(\text{CN})_2]^-$, $[\text{AuCl}_2]^-$, $[\text{Au}(\text{OH})_4]^-$, and $[\text{AuCl}_4]^-$. There is only one naturally occurring isotope of gold: ^{197}Au .

In nature gold occurs predominantly in the native state or as a major constituent of various alloys containing mainly silver, copper or platinoid metals. Several gold and gold-silver tellurides are known of which the most common are sylvanite, calaverite, petzite, krennerite and nagyagite. The antimonide, aurostibite, AuSb_2 , occurs as a hypogene mineral in some auriferous deposits, and there is also a selenide, fischesserite, Ag_3AuSe_2 , and a bismuthide, maldonite, Au_2Bi , which is fairly well differentiated. The principal ore minerals of gold are the native metal, aurostibite and the various tellurides.

The abundance of gold in the upper lithosphere is about 0.005 ppm, and the Au/Ag ratio is about 0.1. The average gold content of igneous-type rocks in parts per million is – ultrabasic (0.004), gabbro-basalt (0.007), diorite-andesite (0.005) and granite-rhyolite (0.003). The average gold content of sedimentary rocks in parts per million is – sandstone and conglomerate (0.03), normal shale (0.004) and limestone (0.003). Certain graphitic shales, sulphide schists, phosphorites and some types of sandstones and conglomerates may contain up to 2.1 ppm Au or more.

The average gold content of soils is 0.005 ppm, and the average for natural fresh waters is 0.00003 ppm. Sea and ocean waters contain an average of 0.000012 ppm Au. Gold is a trace constituent of many plants and animals. Some coals are slightly enriched in gold with 0.05 to 0.1 ppm Au in the ash.

Gold is won both from deposits mined essentially for the element and as a byproduct of the mining and treatment of nickel, copper, zinc, lead and silver ores. The following types of primary deposits, exploited mainly for gold, can be distinguished:

1. Auriferous porphyry dykes, sills and stocks; 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 igneous or granitized rocks.

Résumé

L'or est un élément du groupe 1B du tableau périodique, qui comprend le cuivre, l'argent et l'or. Du point de vue de sa réactivité chimique, l'or rappelle l'argent à certains égards, mais son caractère chimique est beaucoup plus 'noble'. Les principaux états d'oxydation de l'or sont Au (I) (aureux) et Au (III) (aurique). On ne trouve pas ces états d'oxydation sous forme d'aquo-ions en solution, mais surtout sous forme de complexes du type $[\text{Au}(\text{CN})_2]^-$, $[\text{AuCl}_2]^-$, $[\text{Au}(\text{OH})_4]^-$ et $[\text{AuCl}_4]^-$. Il n'existe à l'état naturel qu'un seul isotope de l'or: ^{197}Au .

Dans la nature, l'or se présente généralement à l'état natif, ou allié à d'autres métaux, surtout l'argent, le cuivre, ou les métaux du groupe du platine. On connaît plusieurs tellurures d'or et d'argent, dont les plus communs sont la sylvanite, la calaverite, la petzite, la krennerite et la nagyagite. L'antimoniure, l'aurostibite, AuSb_2 , se présente sous forme de minéral hypogène dans certains gisements aurifères, et il existe aussi un sélénure, la fischesserite, Ag_3AuSe_2 , et un bismuthiure, la maldonite, Au_2Bi , lequel est assez bien différencié. Les principaux minéraux d'or sont l'or natif, l'aurostibite et les divers tellurures.

L'abondance de l'or dans la partie supérieure de la lithosphère est d'environ 0.005 ppm et la proportion Au/Ag est d'environ 0.1. La teneur moyenne en or des roches ignées, exprimée en parties par million, est de 0.004 pour les roches ultrabasiques, de 0.007 pour les gabbros et les basaltes, de 0.005 pour la diorite et l'andésite, et de 0.003 pour le granite et la rhyolite. La teneur moyenne en or des roches sédimentaires, exprimée en parties par million, est de 0.03 pour les grès et les conglomérats, de 0.004 pour les schistes argileux normaux et de 0.003 pour le calcaire. Certains schistes graphiteux, certaines phosphorites, certains schistes cristallins sulfureux, et certains types de grès et de conglomérats peuvent contenir jusqu'à 2.1 ppm de Au ou davantage.

La teneur moyenne en or des sols est de 0.005 ppm et la teneur moyenne des eaux douces naturelles est de 0.00003 ppm. Les eaux marines et océaniques contiennent en moyenne 0.000012 ppm de Au. L'or se présente sous forme d'élément-trace chez de nombreux végétaux et animaux. Certains charbons sont légèrement enrichis en or et leurs cendres contiennent de 0.05 à 0.1 ppm de Au.

On extrait l'or à la fois dans des gisements aurifères proprement dits et dans des gisements où il est un sous-produit de l'extraction et du traitement des minerais de nickel, de cuivre, de zinc, de plomb et d'argent. On peut distinguer les types suivants de dépôts primaires, que l'on exploite surtout pour l'or:

1. Les dykes, sills et stocks de porphyres granitiques aurifères, et les corps granitiques à grain grossier, les aplites et les pegmatites.

2. Les gisements aurifères de type skarn.

3. Les veines, stockworks, filons, colonnes minéralisées et masses irrégulières silicifiées, aurifères-argentifères et argentifères-aurifères, situés dans les fractures, les failles, les zones de cisaillement, les zones à feuillets minéralisés et les zones de brèches, que l'on rencontre surtout dans les terrains volcaniques.

4. Les veines, filons, zones à feuillets minéralisés, et gîtes en selle aurifères, situés dans les failles, fractures, discordances stratigraphiques, et les zones de cisaillement, plis d'entraînement, zones broyées et voûtes anticlinales que l'on rencontre surtout dans les

6. Disseminated and stockwork gold-silver deposits in igneous, volcanic and sedimentary rocks.

(a) Disseminated and stockwork gold-silver deposits in igneous bodies.

(b) Disseminated gold-silver occurrences in volcanic flows and associated volcanoclastic rocks.

(c) Disseminated gold-silver deposits in volcanoclastic 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.

Placers constitute the principal secondary type of gold deposit.

The quartz-pebble conglomerate deposits provide the bulk of the world's production of gold, some 56 per cent. The other deposits, mainly the vein and disseminated types, eluvial and alluvial placers and the various polymetallic veins, lodes, massive bodies and stockworks (byproduct gold) now provide the remaining 44 per cent of the production.

The epigenetic vein, lode, stockwork and disseminated types of gold deposits appear to have originated mainly by metamorphic sequestration processes, the source rocks of the gold and its associated elements being mainly the enclosing volcanic and/or sedimentary piles. Modern gold placers are of sedimentary origin, the gold being winnowed into pay streaks as the result of both chemical (accretion) and physical (gravity) processes operating during weathering and subsequent sedimentation. The auriferous quartz-pebble conglomerate deposits appear to have originated as placers, the gold and many of its associated elements having undergone radical chemical reworking during subsequent diagenetic and metamorphic events.

The oxidation processes in gold deposits are complex and depend essentially on the Eh and pH. Colloidal and coprecipitation phenomena also play a large part. Iron and manganese minerals and carbonates in the gangue and ore greatly influence the reactions that lead to the secondary enrichment of the element. Gold is not easily solubilized in nature, and its soluble forms are readily reduced to the metal by a great variety of natural materials. The result of this behaviour is that the only common gold mineral found in the oxidized zones of auriferous deposits is the native metal. In this form it ultimately collects in both eluvial and alluvial placers, which have been exploited throughout the world since time immemorial.

Practically all the geochemical methods of prospecting are applicable in the search for auriferous deposits. The most effective methods appear to be those based on the sampling of stream and lake sediments and soils, analyzing these materials directly or analyzing heavy mineral separates obtained from them. The most specific indicator (pathfinder) elements for gold are Ag, As, Sb and Te.

terrains sédimentaires; et aussi, les gisements de substitution tabulaires et irréguliers, qui se sont formés à proximité de failles et fractures, dans des lits à caractères chimiques favorables.

5. Les veines, filons, stockwerks, zones silicifiées, aurifères-argentifères et argentifères-aurifères, situées dans un milieu géologique complexe, comprenant des sédiments, des roches volcaniques et des roches ignées ou granitisées.

6. Les disséminations et stockwerks aurifères et argentifères, dans les roches ignées, volcaniques et sédimentaires.

(a) Disséminations et stockwerks aurifères et argentifères dans les corps ignés.

(b) Disséminations aurifères et argentifères dans les coulées volcaniques et les roches associées volcanoclastiques.

(c) Disséminations aurifères et argentifères dans les lits volcanoclastiques et sédimentaires: les gîtes qui se sont formés dans les roches tufacées et les formations ferrifères; et, les gîtes qui se sont formés dans des lits sédimentaires de composition chimique favorables.

7. Les gîtes aurifères que l'on rencontre dans les bankets et les quartzites.

Les placers constituent le principal type de gisements secondaires d'or.

Les bankets (conglomérats contenant surtout des galets de quartz vitreux) fournissent la plus grande partie de l'or mondial, soit environ 56 pour cent. Les autres gisements, surtout les disséminations, veines filoniennes, et placers éluviaux et alluviaux, et les diverses veines filoniennes, filons, corps massifs et stockwerks polymétalliques (où l'or est un sous-produit) constituent actuellement les 44 pour cent restants de la production.

Les types de gisements aurifères épigénétiques, tels que les veines, filons, stockwerks, et disséminations semblent s'être formés surtout par des processus d'imprégnation diffuse au cours du métamorphisme, les roches mères de l'or et des éléments associés étant surtout les colonnes encaissantes volcaniques ou sédimentaires, ou les deux à la fois. Les placers aurifères modernes sont d'origine sédimentaire, l'or s'accumulant suivant des traînées, les 'pay streaks', sous l'effet de processus chimiques (accrétion) et physiques (gravité) qui agissent au cours de l'altération et de la sédimentation ultérieure. Les bankets aurifères semblent avoir été originellement des placers, où l'or et une grande partie des éléments qui l'accompagnent ont subi par la suite un remaniement chimique extrême, par diagénèse et métamorphisme.

Les processus d'oxydation qui ont lieu dans les gîtes aurifères sont complexes, et dépendent essentiellement du Eh et du pH. Des phénomènes colloïdaux et de coprecipitation jouent aussi un rôle important. Les minéraux riches en fer et en manganèse ainsi que les carbonates que l'on trouve dans la gangue et le minerai ont une influence profonde sur les réactions qui aboutissent à l'enrichissement secondaire en cet élément. Dans la nature, l'or est difficilement entraîné en solution, et ses formes solubles sont facilement réduites par un grand nombre de matériaux naturels pour donner l'or métallique. Il en résulte que le seul minerai aurifère que l'on rencontre habituellement dans les zones oxydées des gisements aurifères est le métal natif. C'est sous cette forme qu'il s'accumule finalement dans les placers éluviaux et alluviaux, que l'on exploite dans le monde entier depuis des temps immémoriaux.

Pratiquement, toutes les méthodes géochimiques de prospection conviennent à la recherche de gîtes aurifères. Les méthodes les plus efficaces semblent être celles fondées sur l'échantillonnage de sédiments et sols fluviaux et lacustres, et sur l'analyse de ces matériaux eux-mêmes, ou des minéraux lourds obtenus par séparation. Les éléments indicateurs qui accompagnent le plus fréquemment l'or sont Ag, As, Sb et Te.

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Frontispiece

Native gold, Paymaster Mine, South Porcupine, Ontario (natural size)

Native gold nuggets, Goldrun Creek placer, Cassiar district, British Columbia (natural size)

The gold cups of Vaphio: from the tholos tomb near Vaphio, Laconia, Greece. First Late Minoan, late 16th–early 15th century B.C., National Archaeological Museum, Athens.

The modern (upper left) and alchemical (lower right) symbols for gold, the most noble of metals

The Argonauts examining the Golden Fleece at Colchis.

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Au



The modern (upper left) and alchemical (lower right) symbols for gold, the most noble of metals.

The Argonauts examining the Golden Fleece at Colchis on the Euxine (Black Sea). (From Agricola, *De Re Metallica*.) According to Greek mythology, the Golden Fleece was taken from the ram on which Phrixus and Helle escaped from being sacrificed. It was hung up in the grove of Ares in Colchis and recovered from King Aeetes by the Argonautic expedition under Jason, with the help of the sorceress, Medea the king's daughter. In actual fact the Argonauts were early prospectors who sought the source of the ancient placers on the Black Sea. At that time (1200 B.C.) the workers of auriferous placers recovered the gold by trapping the metallic particles on sheep's fleeces placed in crude sluices. The fleeces were then hung up to dry in nearby trees and were later shaken to collect the gold.

