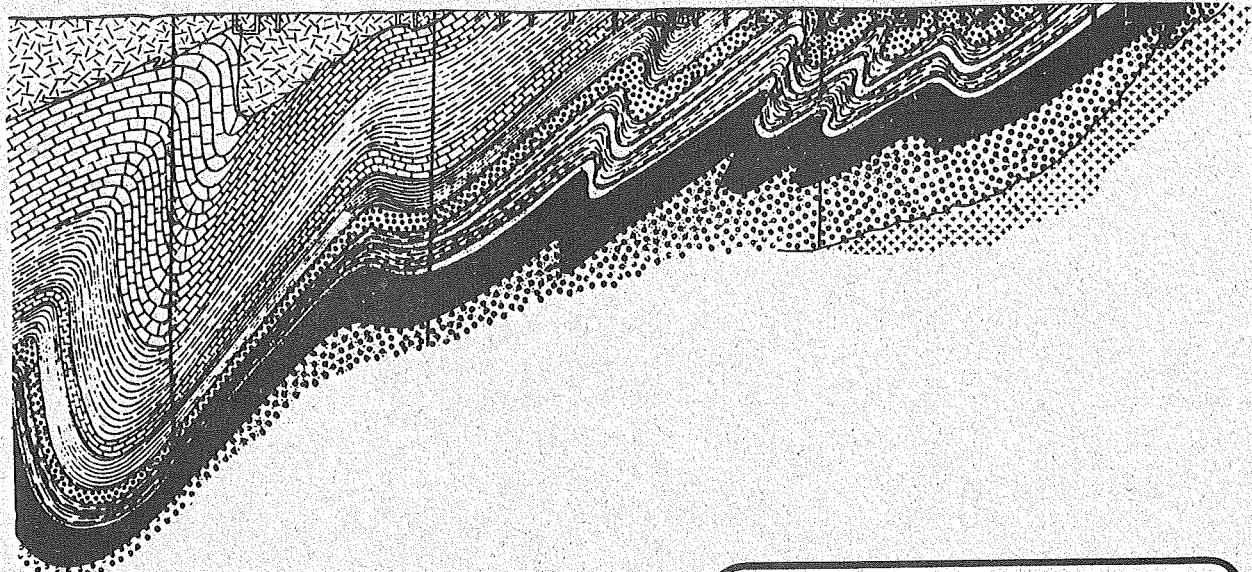




UNIVERSITY OF THE WITWATERSRAND
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ECONOMIC GEOLOGY
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UNIVERSITY OF THE WITWATERSRAND
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A REVIEW OF THE GEOCHEMICAL CHARACTERISTICS
OF GOLD IN ORE DEPOSITS

by

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ABSTRACT

Most of the previous work on gold ore deposits, with special reference to the geochemistry, is reviewed. Gold is shown to be associated with definite minerals and elements in ore deposits, and the mode of occurrence of the gold in sulphide minerals is discussed. Native gold generally has a relatively uniform trace element assemblage, but metallogenetic districts may be characterized by certain elements in the gold. The mode of occurrence of the trace elements in the gold is discussed in the light of metallurgical evidence. The fineness of gold ores is found to vary markedly in both placer and vein deposits. The vertical depth of the gold, its lateral position, the grain size, the grade of ore, and the time and conditions of deposition, all affect the fineness of the gold. The variations in fineness are found to have practical applications. Available information on the gold-copper ratios of ores is also discussed.

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OF GOLD IN ORE DEPOSITS

CONTENTS

	<u>Page</u>
<u>INTRODUCTION</u>	1
<u>ORE MINERALS AND ELEMENTS PRESENT IN GOLD DEPOSITS</u>	4
A. <u>ORE MINERALS ASSOCIATED WITH GOLD MINERALISATION</u>	4
(a) <u>General</u>	4
(b) <u>Australia</u>	5
(c) <u>Canada</u>	5
(d) <u>Congo</u>	6
(e) <u>Finland</u>	6
(f) <u>South Africa</u>	7
(g) <u>U.S.A.</u>	7
(h) <u>Conclusions</u>	10
B. <u>ELEMENTS IN GOLD ORES AND HOST ROCKS</u>	11
(a) <u>General</u>	11
(b) <u>Canada</u>	12
(c) <u>Finland</u>	16
(d) <u>Russia</u>	16
(e) <u>South Africa</u>	17
(f) <u>U.S.A.</u>	19
(g) <u>Conclusions</u>	20
C. <u>MODE OF OCCURRENCE OF GOLD IN SULPHIDE MINERALS</u>	21
D. <u>THE GOLD-COPPER RATIO IN ORES</u>	28

CONTENTS

	<u>Page</u>
<u>E. SUMMARY AND CONCLUSIONS</u>	24
<u>THE CHARACTERISTICS OF NATIVE GOLD IN ORE DEPOSITS</u>	26
<u>A. THE COMPOSITION OF NATIVE GOLD</u>	26
(a) <u>General</u>	26
(b) <u>Alaska</u>	27
(c) <u>Australia</u>	27
(d) <u>Canada</u>	28
(e) <u>Congo</u>	30
(f) <u>England</u>	30
(g) <u>Finland</u>	30
(h) <u>Germany</u>	31
(i) <u>Japan</u>	31
(j) <u>Ruanda-Urundi</u>	31
(k) <u>Russia</u>	32
(l) <u>Southern Africa</u>	33
(m) <u>Conclusions</u>	33
<u>B. THE MODE OF OCCURRENCE OF TRACE ELEMENTS IN NATIVE GOLD</u>	34
<u>C. SUMMARY AND CONCLUSIONS</u>	36
<u>THE FINENESS OF GOLD ORES</u>	39
<u>A. INTRODUCTION</u>	39
<u>B. VARIATIONS IN THE GOLD-SILVER RATIO OF GOLD ORES</u>	41
(a) <u>Alluvial Gold Deposits</u>	41

CONTENTS

	<u>Page</u>
(b) <u>Lode Gold Deposits</u>	43
(i) Vertical Variations in Fineness	43
(ii) Lateral Variations in Fineness	47
(iii) Grain Size and Variations in Fineness	48
(iv) Grade of Ore and Variations in Fineness	50
(v) Fineness Variations and the Period and Conditions of Deposition	52
(c) <u>Practical Applications of the Variations in Gold Fineness</u>	54
C. <u>SUMMARY AND CONCLUSIONS</u>	55
<u>SUMMARY AND CONCLUSIONS</u>	57
<u>LIST OF REFERENCES</u>	59

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A REVIEW OF THE GEOCHEMICAL CHARACTERISTICS OF GOLD IN ORE DEPOSITS

INTRODUCTION

Gold is a siderophile element and tends to be concentrated in iron-rich phases and systems. Thus, it is relatively rare in the lithosphere of the earth and is probably concentrated in the nickel-iron core. The average gold content of meteorites is given by Goldschmidt (1958) as 4 ppm. and 0.7 ppm. for nickel-iron meteorites and troilites respectively. Fleischer (1953) indicated the abundance of gold in the earth's crust as varying between 6×10^{-7} and 1.5×10^{-7} per cent by weight. Woodtli (1960) showed the average concentration of gold in the crust to be 0.0000n gm/ton.

The amount of gold present in various igneous rock types varies considerably. For the two standard igneous rocks G.1 (a granite from Westerby, Rhode Island) and W.1 (a diabase from Centerville, Virginia), Ahrens and Fleischer (quoted by Ahrens and Taylor, 1961), gave the gold content as 0.01 and 0.018 ppm. respectively. Lincoln (1911) discussed certain natural associations of gold in both rocks and minerals. He presented data on the gold and silver content of 48 igneous rocks and concluded that they contained minute amounts of the two elements in extremely variable concentrations. The gold showed no preference for either acid or basic rocks, but silver had a slight tendency to concentrate in basic rocks.

The gold content of sub-crustal waters, veins, surface waters and salts, organic material and sedimentary rocks was also discussed. The average content of all sedimentary rocks was shown as 15 mgm/ton and it was concluded that, the coarser the sedimentary rock, the greater the amount of gold present. Lincoln's conclusions as regards the origin of lode gold presented five possible sources in the following order of importance:

- (i) "depressed beds of open-textured sediments;
- (ii) depressed beds of open-textured tuffaceous rocks;
- (iii) fractured older lodes;
- (iv) fractured compact igneous rocks; and
- (v) fractured compact sedimentary rocks".

Vincent and Crocket (1960a) in a study of the distribution of gold in the Skaergaard rocks and minerals, found that the chilled marginal

gabbro (representing the original magma) contained 0.0046 ppm. gold; but most of the other rocks in the intrusion also had gold contents of this order of magnitude. They reported that the gold, which they concluded to be present as uncharged atoms, showed no preference for any of the various silicates, oxides or iron sulphide minerals, but was very strongly concentrated in the copper sulphides, emphasising the chemical similarity of the copper and gold atoms. In a second paper Vincent and Crocket (1960b) showed concentrations of 0.002 ppm. gold in basalts; 0.001 - 0.01 ppm. in dunites and olivine-rich nodules in basalts; and 0.01 - 0.3 ppm. in chondritic meteorites in which most of the gold was concentrated in the dispersed metallic phase.

Acid rocks from the Bushveld Complex were found to contain 9.2 ppm. gold according to Hagen (1954). The basalts contained 11.0 ppm., the gabbros 8.7 ppm., and the peridotites, pyroxenites, anorthosites and norites 6 - 7 ppm.

For further details on the concentration of gold in rocks, Goldschmidt (1958) and Rankama and Sahama (1955) should be consulted. Both references give comprehensive summaries of reported results.

Gold is found in soils in varying concentrations, and may be present in amounts large enough to be detected by geochemical prospecting, (Sokoloff, 1950). Hanna and Wolff (1941) found gold in salt dome cap-rocks. I. and W. Noddack (1939, quoted by Goldschmidt, 1958) reported 8×10^{-6} ppm. gold in sea water. The element has been indicated in plants (Goldschmidt, 1958; Warren and Delavault, 1950), and in human beings (Zviagintsev, quoted by Rankama and Sahama, 1955).

Thus, it can be seen from the above brief summary of the distribution of gold, that the element occurs sporadically in very small amounts throughout all phases of the earth. In ore deposits, however, gold tends to be concentrated in amounts greater than those quoted above, and it has been found to be associated with definite minerals or elements, and to vary in composition and abundance with certain physical factors.

In nature, gold normally occurs as the native metal, usually alloyed with some silver and containing small amounts of copper and other base metals. The only relatively common natural compounds of gold are the telluride minerals, such as calaverite and sylvanite. Maclaren (1908) presented chemical analyses of some of these gold minerals, the most interesting of which were:

Mineral	Source	Au	Ag	Te	Base Metals
Calaverite	Kalgoorlie	38.70%	1.66%	58.69%	Cu, Fe, S, Pb, Bi, Zn.
Calaverite	Kalgoorlie	37.54	2.06	58.63	Cu, Fe, Ni, Se, S.
Sylvanite	Offenbaya	26.97	11.47	59.97	Cu, Pb, Sb.
Sylvanite	Nagyag	26.08	11.57	61.98	Cu, Fe, Pb.
Mullerine	Nagyag	24.89	14.68	55.39	Pb-2.54%, Sb-2.50%
Nagyagite	Nagyag	contains Te, S, Sb, Pb, Au, Ag, Cu.			

The results reflected the large number of elements with which gold might be associated in one compound, and also indicated the elements which could be expected to occur in trace amounts in native gold. Very rarely alloys such as gold amalgam (Au-Hg), maldonite (Au-Bi), gold-copper and gold-palladium are found.

ORE MINERALS AND ELEMENTS PRESENT IN GOLD DEPOSITS

A. ORE MINERALS ASSOCIATED WITH GOLD MINERALISATION

(a) General

Lincoln (1911) discussed the natural associations of gold and listed data from 585 gold vein deposits throughout the world. From this information he concluded that pyrite, galena, chalcopyrite, argentite, pyrrhotite and silver were the most common associates of gold (in order of decreasing importance). Gold tended to precipitate most readily when in contact with the following minerals: lollingite, bismuth, tetradyomite, calaverite, hessite, bismuthinite, pyrite, jamesonite, pyrrhotite, tetrahedrite, argentite, chalcopyrite, stibnite and sphalerite.

Schwartz (1944) published a review of the host minerals of native gold, in which he dealt with information made available since Lincoln's paper. He found that gold occurred in direct contact with the following minerals: pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, bismuth minerals, pyrrhotite and tetrahedrite-tennantite (in decreasing order of importance). The most common gangue minerals were quartz, carbonate, chlorite, graphite, carbonaceous material and tourmaline. Available data suggested that only a few minerals were effective precipitants of gold under natural conditions, though the possibility of precipitation by the host was not denied. Variability in the relation of the gold to the host was common.

A paper by Bruce (1934) described a spectrographic study of quartz from gold-bearing veins, with special reference to coloured varieties of quartz which seemed to be related to areas of high gold values. It was found that the colouring was not due to the presence of any particular element, but to the state of ionisation of a particular element, or even to the state of the silicon itself. The association of high concentrations of gold with blue or grey quartz seemed to be more than coincidence and it was thought likely that the conditions which caused the colouring of the quartz (i.e. changing of the state of the trace colouring element) might also have caused the deposition of gold from the ore fluids in exceptional quantities.

(b) Australia

Don (1897), in a paper dealing with the genesis of auriferous lodes, experimentally tested previously suggested theories by detailed analysis and study of the ores and country rock in the South St. Mungo Mine, Bendigo, Australia, where he noted a striking relation between the amount of sulphide mineralisation and the gold content of the ore. In statistical plots he verified the observations and proved that a high sulphur content in the ore indicated a high gold content.

Pyrrhotite was the main constituent of the ore of the Hill 50 Gold Mine (Edwards, 1955). Minor constituents included pyrite, chalcopyrite, galena and gold. The gold was genetically related to the sulphides and showed a preference for pyrite and chalcopyrite over pyrrhotite. Edwards also observed that the grade of ore varied remarkably with depth: from 120 to 300 feet the average grade was 7.5 dwts Au/ton; from 300 to 400 feet, 4.9 dwts/ton; at 600 feet, 4.5 dwts/ton; and from 820 to 1,060 feet, 14 dwts/ton.

(c) Canada

Warren and Cummings (1937) dealt with the relationship between gold and metallic minerals in British Columbia. From a mineralographic study they found that in different areas the gold was associated with different minerals, the most common being pyrite, pyrrhotite and arsenopyrite. This association provided a simple means of classification of the deposits. However, in no case was the gold found to be chemically related to any particular sulphide. In the higher temperature deposits, the gold tended to show contemporaneous deposition with the associated sulphides, while in low temperature deposits it was, for the most part, definitely younger.

Blomfield, et al, (1936) described the ore of the Lake Shore Mine, Canada, and quoted Haycock as reporting the presence of the following minerals in the ore concentrate: pyrite, chalcopyrite, petzite, molybdenite, sphalerite, galena and altaite. By plotting graphs of the concentrations of the various minerals in individual samples, it was shown that the gold content was not proportional to the pyrite content, but appeared to be related to the amount of chalcopyrite present. However, the chalcopyrite content in the ore was so low that it could not account for all the gold. The authors concluded, independently of Haycock's results, that pyrite was the dominant ore mineral.

Variations in the associated minerals with depth were reported by Thompson (1941) from the Kerr-Addison Mine, Ontario. Pyrite, the most abundant ore mineral, showed a slight decrease in concentration below the 700 feet level; arsenopyrite, the next most abundant ore mineral, increased in content from the 700 feet level downwards; chalcopyrite was a minor constituent down to the 700 feet level and then disappeared. Carbonates and quartz were the most abundant gangue minerals.

The most abundant sulphide minerals in the Yellowknife gold deposits, Northwest Territories, Canada, according to Boyle (1961), were pyrite, arsenopyrite, sphalerite, chalcopyrite, stibnite, sulphosalts, pyrrhotite, galena and molybdenite. Gold and aurostibnite were the main economic minerals. Scheelite, tourmaline and hematite were also found in the deposits. All the elements which constituted the sulphide minerals were detected in the country rocks in amounts sufficient to account for the sulphides in the deposits. Therefore Boyle suggested that the sulphides were concentrated in the veins during shearing, when the elements concerned migrated from the country rock into dilatant zones. The gold and silver in the rocks were thought to have behaved in a similar manner. Gold was spectrographically detected in pyrite, arsenopyrite, stibnite and sulphosalts, such as freibergite. In the country rock the gold and silver were concentrated in pyrite, chalcopyrite and pyrrhotite, the silver content varying from 1 to 10 ppm. and the gold content from 0.1 to 0.5 ppm.

(d) Congo

Gold from eastern Urega in the Congo was reported by Van Aubel (1935) to be associated with arsenopyrite, pyrite, marcasite, dravite and graphite. Galena, sphalerite and chalcopyrite occurred occasionally.

(e) Finland

Saksela and Heiskanen (1952), in discussing the gold occurrences in the Valkealeoski area, Finland, reported that arsenopyrite, lollingite and magnetic pyrite were the main sulphides associated with the gold.

7/...

(f) South Africa

Frankel (1939), in a study of the Black Reef, found over 40% of the gold to be intimately associated with pyrite. The gold had a pale yellow colour and was rich in silver, up to 49% silver being obtained on assay of the ore. These results seemed to indicate the presence of electrum or some silver-rich mineral, such as argentite, or a telluride.

De Villiers (1957) dealt with the chemistry and mineralogy of the Barberton gold deposits. Table 1 summarizes the results of the mineralogical study. The ore deposits were divided into four types; the arsenopyritic and pyrrhotitic ores; the lead-bearing ores; the antimonial ores and the pyritic ores. Native gold was found associated with all four types of ore. Arsenopyrite and pyrite, with chalcopyrite in minor amounts, were the most common sulphide minerals. Of the other minerals present in the area, it is interesting to note that a telluride, tetradyomite, was recorded in the Golden Quarry Mine; that an unidentified platinoid-bearing mineral occurred in the Eagles Nest Mine; and that native silver was found in the Rosetta and Golden Quarry Mines.

(g) U. S. A.

Collins (1902), dealing with the gold-silver ores of Gilpin Co., Colorado, noted that, although the gold and silver were associated with sulphide mineralization, the values were greatest when the particular sulphide was mixed with quartz and with other ore minerals. The values did not seem to be concentrated in a particular mineral, though the gold was thought to be associated with copper ores, while the silver with lead ores. In both cases the values decreased as the proportion of quartz increased.

Hulin (1930) found gold from the 3,900 feet level of the Kennedy Mine, California, to be associated mainly with galena and chalcopyrite. Apatite and carbonates were also commonly associated with the gold, while pyrite, sphalerite and quartz showed little relationship to the gold.

Gold ores at Goldfield, Nevada, were reported by Wilson (1944) to be associated with alunite. Other ore minerals included pyrite, famatinite, bismuthinite, marcasite, sphalerite, wurtzite, tennantite, goldfieldite and tellurides. Tapp (1948) found that the

8/...

TABLE 1a.

ORE MINERALS OF THE BARBERTON DISTRICT

(After de Villiers, 1957)

	Ores with arsenopyrite-pyrrhotite		Ores with antimony		Ores with lead		
	Lily	Eagles Nest	New Consort	Amo	Bellevue	Rosetta	Alfström
Arsenopyrite	3	2	2		1		
Antimony				1			
Berthierite			1				
Bismuth			tr				
Bournonite					tr		
Chalcocite							
Chalcopyrite	1		3	tr	2		
Cobaltite							
Corynrite					tr		
Covellite							
Enargite				tr			
Galena			tr		3	3	
Gold	1		2	tr	1		
Jamesonite				tr			
Magnetite	1						
Marcasite		1					
Maucherite		tr					
Melnikovite-pyrite	3						
Niccolite		tr					
Pentlandite		1					
Platinoid minerals		1					
Pyrite	3		1	2	3	1	
Pyrrhotite	3	1	3				
Silver					tr		
Sphalerite					3	2	
Stibnite		2	3	3			
Tetradymite					2		
Tetrahedrite							
Trevorite			tr				
Violarite					tr		

3 - very abundant; 2 - common; 1 - rare; tr - trace amounts

TABLE 1b.

ORE MINERALS ASSOCIATED WITH PYRITIC ORES
OF BARBERTON DISTRICT (after de Villiers, 1957)

	Alpine	Agnes	Three Sisters	Fairview	Sheba	Golden Quarry	Sheba Queen
Arsenopyrite				2	2	2	1
Antimony							
Berthierite							
Bismuth							
Bournonite						1	
Chalcocite							
Chalcopyrite	1	1	tr	1	1	tr	
Cobaltite							
Corynrite	tr					tr	
Covellite						1	
Enargite							
Galena	1						tr
Gold	1	1	1	tr	2	1	tr
Jamesonite							
Magnetite							
Marcasite							
Maucherite							
Melnikovite-pyrite							
Niccolite							
Pentlandite							
Platinoid minerals							
Pyrite	2	3	2	3	3	3	3
Pyrrhotite					1		tr
Silver							tr
Sphalerite	1	1					
Stibnite							
Tetradymite							tr
Tetrahedrite	1					1	
Trevorite							
Violarite	1						

TABLE 1c.

ORE MINERALS ASSOCIATED WITH PYRITIC ORES
OF BARBERTON DISTRICT (after de Villiers, 1957)

	Comstock	Forbes Reef	Barbrook	Belfast	Clutha	Piggs Peak
Arsenopyrite	2		2		2	1
Antimony						
Berthierite						
Bismuth		tr				
Bournonite						
Chalcocite						
Chalcopyrite	1	1	tr	1	1	1
Cobaltite					tr	
Corynite						
Covellite						
Enargite						
Galena						
Gold	tr	tr	1	1	tr	tr
Jamesonite						
Magnetite						
Marcasite						
Maucherite						
Melnikovite-pyrite			tr			1
Niccolite						
Pentlandite						
Platinoid minerals						
Pyrite	2	2	3	1	3	3
Pyrrhotite	tr		1	1	1	1
Silver						
Sphalerite						
Stibnite						
Tetradymite						
Tetrahedrite						
Trevorite						
Violarite						

11/...

gold in the North Empire mining district, Colorado, was associated with primary and secondary copper minerals, which disappeared with depth.

(h) Conclusions

From the above examples it can be seen that, for individual deposits, the important ore minerals differ, though pyrite, chalcopyrite, arsenopyrite, pyrrhotite and galena are most commonly present. One interesting conclusion is that it is not always the most abundant associated minerals which are related to the high gold values. Also of possible significance is the fact that gold often shows a tendency to concentrate with copper minerals, such as chalcopyrite.

B. ELEMENTS IN GOLD ORES AND HOST ROCKS

(a) General

Lincoln (1911) found that, excluding iron and lead in the form of pyrite and galena, the most common elements associated with gold were arsenic, bismuth, selenium and tellurium.

The trace elements in pyrite, pyrrhotite and chalcopyrite from nickel, copper and gold ore deposits were found by Hawley and Nicholl (1961) to include Co, Ni, Ag, Cr, Pb, Sn, Ti, V, Au, As, Bi, Mn and Mo. Co, Ni, Ag and Pb showed a specific order of preferential concentration in the three sulphides. Variations in the quantities of trace elements present in the individual minerals were apparent in both different and similar types of deposits and in sulphides of different generations. Qualitatively there was a striking similarity in the trace elements in the sulphides of all deposits. This similarity suggested a magmatic source for the ores, with local contamination of ore fluids as a cause of the variations.

Fleischer (1955) reviewed most of the work done on minor elements in sulphides. Suggested modes of occurrence of minor elements and trace minerals in the sulphides included isomorphous substitution, absorption, oriented overgrowths, oriented intergrowths, and inclusions. The concentrations of the trace elements in the sulphides were affected by temperature and pressure conditions at the time of formation, by regional factors, and by the types of wall-rocks and associated igneous

12/...

rocks. However, for formation temperatures to have affected the minor element concentration, equilibrium concentrations of the minor elements must have been attained. The minor elements in galena, sphalerite, wurtzite, chalcopyrite, pyrite, marcasite, pyrrhotite and arsenopyrite were described.

(b) Canada

Haycock (quoted by Blomfield, et al, 1936) detected the following elements in concentrates from the Lake Shore mine : iron, copper, silicon, magnesium, calcium, gold, molybdenum, tellurium and lead. The first five elements were essential constituents, giving moderate to strong spectra, while the last four all showed strong traces. Spectrographic analysis of pyrite from the concentrate showed no gold lines, and Haycock suggested that the concentration of gold was less than 3 ozs./ton pyrite (the limit of detectability). Blomfield and co-workers independently found the average concentrate to contain molybdenum sulphide, carbon, lead, zinc, copper, iron, tellurium, sulphur, arsenic and gold.

Elements associated with the gold in the ores of the Yellowknife district included Ag, Fe, S, As, Sb, Cu, Pb and Zn, (Boyle, 1961). Pyrite in the ore tended to collect the chalcophile elements, such as Ni, Co, Cu, Zn, Mn, Pb, As, Sb, Ga, Sn, In, V, Ag and Au, all of which probably occurred in the pyrite lattice. Arsenopyrite also collected the chalcophile elements, especially Co and Ni, and Sb. Pyrrhotite appeared to have a low tolerance for extraneous chalcophile elements, only Ni, Cu and Co being commonly present.

Auger (1941) investigated the zoning and variation of minor elements in pyrite of Canadian gold deposits. By ensuring the purity of the samples, he eliminated the possibility of any trace elements being present as inclusions. By comparing the atomic nucleus, valence, atomic radius and atomic weight of all the elements, he concluded that the most common minor elements, especially those of the nickel-iron-cobalt group, were included in the pyrite lattice by substitutional solid solution. He suggested also that the crystal habit might have had an affect on the distribution of the minor elements in the pyrite.

Auger's detailed analytical results of 124 samples, both within and outside the Precambrian Shield, showed that, within the Shield

the minor elements were very similar in quantity and quality in all the deposits, the iron, nickel and cobalt group appearing in nearly every sample in appreciable quantities. Within one district, or mine, the apparent supremacy of one element over another was very consistent. For example, in most ores silver predominated over lead and zinc, but at Hollinger the relative ratios varied with depth. The results also showed that within one mine there might be a consistent ratio between the intensities of the spectral lines of the minor elements and that while this ratio might be consistent over a whole district, the rarer elements were confined to the particular mine. The results indicated that the type of ore deposit had a definite bearing on the nature and proportion of the minor elements present in the pyrite. For example, comparing massive sulphide and vein deposits, it was seen that silicon and indium were present in the former but absent in the latter, while chromium and molybdenum showed the reverse distribution. Variations also occurred between low temperature and high temperature veins as follows:-

	Low Temperature Veins	High Temperature Veins
Cr	absent	abundant
Mn	"	"
Ni	"	Hypothermal
Co	"	"
Pb	abundant	absent (or low)
Zn	"	Mesothermal
Ag	"	"

In other words, the minor elements in the pyrite reflected the type of mineralisation and indicated conditions of deposition. The elements lead, zinc, silver and gold were found only in pyrite in deposits containing at least one of these elements in economic quantities. The wall-rock and gangue material were found to have no effect on the distribution of the minor elements in the pyrite, thus indicating that the total composition of the pyrite was mainly dependent on the nature of the ore solutions.

In addition, detailed studies were made of the variation in minor elements within the individual deposits of the Hollinger, Noranda and Siscoe mines. These variations probably reflected changes in the conditions of equilibrium of the ore fluids from which the pyrite was deposited. Temperature appeared to have been an important variable, since the low temperature metals decreased with depth. In the Hollinger

Mine, however, silver had maximum deposition at greater depth than lead, zinc or chromium, a result which was contrary to the accepted order of deposition of the elements. Results from the Noranda upper and lower ore-bodies indicated that the two bodies were disconnected in time of deposition and were separate units. Similarly, at Siscoe, minor elements in pyrite from three separate veins, previously thought to be contemporaneous, indicated that the veins could have been of different ages. Silver in the gold-quartz veins (Hollinger) had a maximum at intermediate levels, while in the massive sulphide deposit (Noranda), the maximum concentration was at the base of the deposit. Zinc showed a similar variation to silver, but lead, while varying in amount in the veins, was constant in the massive sulphide deposit.

Nickel, but not cobalt, displayed the same variations in both deposits. The various differences were suggested to be due to the fact that the massive ore body was much more homogeneous than the veins. Different portions of an individual vein probably represented different periods of deposition, a likely cause for the variation in minor element content of pyrite.

Warren and Thompson (1945), when studying trace elements in sphalerites from Western Canada, found an apparent relationship between the depth to which gold and silver ore bodies persisted and the amount of manganese present in the associated sphalerite. Out of twenty-five mines investigated, only five extended to depths greater than 1,500 feet and in these the sphalerite contained little or no manganese. The deposits persisting to shallow depths only, contained manganese-rich sphalerite. The relationship was explained by considering the solubility of gold in the presence of MnO_2 and acids, such as HCl , H_2SO_4 and H_3PO_4 . Precipitation of sphalerite from hypogene solutions and, with it, the associated manganese necessary to keep the gold in solution, could have caused the sudden precipitation of the gold over a restricted area. In Tertiary deposits, such as the ones examined, the zone of precipitation would naturally have been related to the present surface, thus accounting for the petering out of the veins at restricted depths. From their results, the authors concluded that a relatively manganese-rich sphalerite indicated that the gold or silver deposit in which it occurred possibly did not persist to depths greater than 1,000 - 1,500 feet.

Pyrite from different types of deposits was examined for its trace element content by Hawley (1952). The deposits included the Powell Rouyn quartz vein, Quebec, the Kerr-Addison Mine, Ontario,

(both worked to 2,500 feet), seven Kirkland Lake mines working to 5,000 feet, and a mine in the Porcupine district working to 5,378 feet. For the Powell Rouyn pyrite, the temperature conditions during deposition were found to be relatively uniform throughout. Of the trace elements, gold and silver decreased vertically and smaller decreases with increasing depth were noted for bismuth, chromium, lead and molybdenum. There was a more marked decrease for manganese, while cobalt and nickel increased with depth. Tin and vanadium showed no change with increasing depth. The coarser-grained pyrite was found to be richer in silver, lead and bismuth than the fine pyrite; the gold content was the same in both; cobalt, chromium, molybdenum and tin were more concentrated in the finer material.

In the flow-type ore of the Kerr-Addison Mine, gold and silver in the pyrite were found to increase with depth, while the cobalt and nickel decreased. The other trace elements, chromium, manganese, lead, molybdenum, tin and arsenic, showed only slight increases in the lower half of the mine. For the three ore-bodies studied in the mine, the minor element content of the pyrite was found to be very similar quantitatively. The differences in grain-size of the pyrite appeared to have some connection with the variations in trace element content, the finer-grained pyrite being richer in gold and silver than the coarser material. Pyrite from quartz veins and wall-rock had the same composition. No marked differences in composition were found in pyrite samples giving different temperatures of formation, though samples showing the same temperatures had similar trace element contents. The results indicated that all the pyrite was deposited under similar conditions from one ore fluid.

Twenty trace elements were reported in the pyrite from the Kirkland Lake mines, of which gold, silver, tellurium, lead, copper, titanium, aluminium, magnesium, barium and strontium were possibly related, in part, to minute inclusions. Little zinc, tin and arsenic were found, while antimony, bismuth and vanadium were absent. The wall-rock seemed to have had a slight affect on the trace element content. For example, in the syenite intrusives, the pyrite was richer in gold, silver and cobalt than elsewhere; pyrite from tuffs was very rich in silver and copper, but poor in lead and gold. With regard to variations with depth, cobalt increased slightly downwards, though its concentration remained constant at both the east and west limits of the belt; gold, tellurium, silver and lead were greatest in the 1,000 - 3,000 feet range; gold and lead were present in the same amounts on

the lowest levels; tellurium was constant from 3,500 to 6,150 feet, while silver decreased with depth. However, the results did not indicate any marked change in the general conditions of mineralisation throughout the gold belt to a depth of 6,000 feet.

In pyrite from the Porcupine district, cobalt and nickel were found to be richest in the finest-grained pyrite, and titanium and arsenic in the coarse material. Pyrite, which gave a high temperature of formation, contained less gold, silver, arsenic, lead and zinc but more cobalt, nickel and tin than the lower temperature material. The distribution of the gold in the pyrite suggested that only trace amounts were deposited originally and that subsequent enrichment had occurred. The highest gold content was found in samples from the 1,500 to 3,750 feet levels. Gold, silver, nickel and lead were higher in pyrite from veins in quartz porphyries rather than from veins in volcanic rocks or slates. Molybdenum, vanadium, manganese and arsenic were present in the same amounts in both types of veins. Gold and silver were found to decrease slightly to depths of 5,000 feet while cobalt, nickel and lead increased.

Trace elements common to all four types of deposits were gold, silver, nickel, copper, chromium, manganese, molybdenum, vanadium, lead and titanium. In most samples cobalt was present in smaller amounts than nickel. In all the deposits the relative uniformity in composition of the pyrite to depths of 6,000 feet was marked. The two deposits which were mined to 2,500 feet showed opposite variations with depth.

(c) Finland

Saksela and Heiskanen (1952) spectrographically analysed an ore mineral (bismuthinite) from the Valkaeleoski area, Finland. Their results were as follows: Au (0.1%), Bi (0.1 - .1%), Te (.001 - .01%), Ag (.001 - .003%), Sn, Sb, Zn, Mn, Hg.

(d) Russia

Zemel (1935) spectrographically analysed 42 samples of gold slimes from various Russian mines and reported the presence of Zr, W, V, Ti, Th, Mo. In a later paper Zemel (1936) presented the results of similar work on gold ores from the Khyuchevskiy, Darasuon, Baleisk, Rifmanovskii and Artemosk mines, showing the presence of Bi, Co, Ni,

Mo, Se, Tl, In, Ga, Cu, Ge, Pb, Te, Sn, Zn, As, Sb, S and Fe. Bi, Te, Co, Mo and Sn tended to concentrate in the ore, especially the last three elements, but this was not the case with Tl, Ga, Ge and In. Some of the rare elements were present in the ores in payable amounts.

(e) South Africa

The gold ores from the Barberton district were spectrographically and chemically analysed by De Villiers (1957). The results are shown in Tables 2 and 3. The concentrations of the individual elements in each sample were indicated by estimating the intensity of the individual analysis lines, the intensities being expressed in numbers from 1 to 10. It must be remembered, however, in using these results, that the intensities of the lines depend on the spectral sensitivity of the elements emitting the lines and therefore the relative concentrations of the elements cannot be obtained from the results. De Villiers did not report copper as being present in any of the concentrates. This element, with silver, is believed to be consistently associated with native gold. The presence of tungsten was unusual and was probably due to the presence of a mineral impurity. Selenium and tellurium were each reported from one deposit only; molybdenum was present in two concentrates. The results of the chemical analyses showed the presence of copper, probably as an associated sulphide. Silver was reported only in trace amounts, indicating that it was present probably in the gold alone and that it did not occur as an independent mineral.

De Villiers concluded from his results that the Barberton gold ores were genetically related to the Nelspruit granite. All the deposits seemed to have been formed at great-to-moderate depths. The New Consort and Lily ores were deposited at high temperatures and great depths, having mineral assemblages similar (except for arsenopyrite) to those of the magmatic sulphide deposits of the Bushveld Complex. The pyritic deposits constituted the major proportion of the Barberton deposits and were mineralogically uniform and characteristically hypothermal. The Rosetta Mine was mesothermal in nature and the ore of the Alfstrom and Alpine mines also showed some mesothermal features. The antimonial ore seemed to have been deposited during the later stages of hydrothermal activity, but at the same depths as the higher temperature minerals. The paragenetic sequence for the pyrrhotite-arsenopyrite ore was (1) arsenopyrite, (2) pyrrhotite, (3) chalcopyrite; for the pyritic ore it was (1) arsenopyrite, (2) pyrite, (3) arsenopyrite.

Concentrate	Ag	Au	Sb	As	Ni	Co	Bi	Zn	Pb	W	Mo	Te	Se	Sn
Rosetta Mine	6	4	4	0	1	1	0-1	6	4	0	0	0	0	0
Rosetta Mine, richest fraction	6	6	5	0	0	1	1	6	5	0	0	0	0	0
Agnes Mine	4	3	0	0	4	3	0	0	2	0	0	0	0	0
Fairview Mine	6-7	8	1	8	3	4	0	2-3	0	1	0	0	0	tr
Fairview Mine, gravity concentrate	3	4	2	8	1	1	0	0	2	0	0	0	0	0
Fairview Mine, flotation concentrate	2	3	0	5	2	3	0	0	0	0	0	0	0	0
Alpine Mine	5	6	4	1-2	6	6	0	0	3	0	0	0	0	0
Sheba Mine	5	5	1-2	2	5	5	0	0	0	0	0	0	0	0
Sheba Mine, richest fraction	7	7	1	4	4	3	0	0	1	5	0	0	0	tr
New Consort Mine	5	4-5	3	8	7	6	0	0	0	0	0	0	0	0
New Consort Mine, richest fraction	9	8	3	6	6	5	0	0	3	3	0	0	0	0
Golden Quarry Mine	6-7	8	0	2	2	1	0	0	1	0	0	0	0	0
Golden Quarry Mine	5	8	0-1	8	4	1	0	0	2	-	0	0	0	0
Three Sisters Mine, corduroy concentrate	5	4	0	0	2	4	0	0	0	0	0	0	0	0
Three Sisters Mine, middlings	6-7	7	0	0	1	3	0	0-1	0	0	0	0	0	0
Piggs Peak Mine	6	7	2	10	6	4	0	0-1	1	0	0	0	0	tr
Woodstock Mine	6	5	1	1-2	7	6	0	0	2	1	0	0	0	tr
Mamre Mine	0	0	0	0	0-1	1	0	0	0	0	0	0	0	0
Mamre Mine, richest fraction	8	6	2	2	1	5	8	0	4	0	2	tr	0	0
Rietfontein (Sabie) Mine, richest fraction	2	1	0	4	0-1	2	0	0	0	0	0	0	0	0
Rietfontein Mine, (Sabie)	1	0	0	2	0	1	0-1	0	0-1	0	0	0	0	0
Forbes Reef	0	0	0	0	0-1	0-1	0	0	0	0	0	0	0	0
Forbes Reef, Western workings	0	0	1	0	1	0	0	0	1	0	1	0	tr	0

Note: Ge, Tl, platinum metals were looked for but not found in any concentrate.

TABLE 2 : ELEMENTS IN GOLD CONCENTRATES FROM BARBERTON DISTRICT (after De Villiers, 1957)

19/...

Concentrates	Ag	Sb	Zn	Pb	Cu	As	Ni	Co	Fe	S	Au
Rosetta Mine, richest fraction	tr	0.41	0.17	8.9	0.3						
Alpine Mine	tr	0.67		tr	0.17	tr	0.15	0.16			
New Consort Mine	0.13			0.05	23.8	1.19	0.36				
Three Sisters Mine, middlings	tr				0.01						
Rosetta Mine	tr	0.47	0.09	9.5	9.3		tr		43.12	30.38	88oz/ton

Table 3 : Chemical Analyses of Gold Concentrates from Barberton District (after De Villiers, 1957).

(4) pyrrhotite and chalcopyrite; for the lead-bearing ore it was (1) pyrite, (2) sphalerite, (3) tetrahedrite, (4) chalcopyrite and galena; for the antimonial ore it was (1) pyrite or arsenopyrite, (2) berthierite and marcasite, (3) stibnite, (4) antimony. Free gold occurred late in the paragenetic sequence, except, perhaps, in the pyrrhotite and arsenopyrite ores where the gold was usually enclosed in the arsenopyrite.

Spectrographic analyses of samples of high- and low-grade pyritic gold ore from Barberton were carried out by Steele and Carlton (1961). Their results were as follows:

	Ag	Al	Au	Cu	Fe	Mg	Mn	Ni	Pb	Si	Sn	As
High-grade ore :	T	M	T	VW	VS	S	M	VW	T	VS	W	W
Low-grade ore :	W	M	T	VW	VS	S	M	VW	-	VS	M	W

VS - very strong; S - strong; M - moderate; W - weak;
VW - very weak; T - trace; - not detected.

Chemical enrichment by concentration of various groups of metals by precipitation and chromatographic separations, showed the high grade ore to contain B, Bi, Cd, Co, Cr, Mo, Sb, Zn. The low-grade ore contained Bi, Cd, Co, Cr, Mo, Pb, Sb, Zn.

(f) U. S. A.

Wilson (1944) made a geochemical study of the epithermal gold deposits at Goldfield, Nevada. These vein deposits occurred in Tertiary

20/...

acid volcanic rocks; they were highly silicified and brecciated and wall-rock alteration was very extensive. Channel samples were collected along the 830 feet level of the Consolidated vein, the 225 feet level of the Clermont vein, and in the hanging-wall of the Jumbo vein, to determine changes as the veins approached the surface. Samples were also taken of the associated wall-rocks. The results of the spectrographic analyses showed that in the vein material a sympathetic relationship existed between the silver, gold, bismuth and tin on the 830 feet level. This relationship persisted horizontally along the vein. On the 225 feet level no quantitative relationship between the above four elements was evident, tin and bismuth being either absent or present in very small amounts, and the gold and silver being independent of each other. Similar results were obtained from samples taken nearer the surface; no tin or bismuth was found, though some silver was present. It was, therefore, concluded that between the 830 feet level on the Consolidated vein and the 225 feet level on the Clermont vein, some change in the character of the ore solutions had occurred.

The constituent elements in the samples taken to study the affect of wall-rock alteration, showed a great diversity in distribution. Manganese and magnesium displayed a very large and abrupt increase in concentration just beyond the contact of the highly altered wall-rock (i.e. away from the vein). Sodium and calcium contents gradually increased away from the vein, but the other elements showed no definite change. The cobalt content increased in the altered wall-rock near the Clermont vein. These results showed that magnesium and manganese were strongly leached from the wall-rock into the vein while sodium and calcium were only moderately extracted by the vein.

Gold ores from veins in California were studied spectrographically by Fuller (1942), and Cook (1947) gave details of the results. It was found that the minor impurities (mostly Ag, Bi, Pb, Sn) in the vein quartz showed no significant correlation with the high-grade ore. This result agreed with those obtained by Bruce (1934). Outside the high-grade areas gold was no more abundant than the trace elements. Assays showed a very abrupt transition in gold content from the high-grade to the barren areas, with a slight tendency for the values to run lower as the high-grade areas were approached.

(g) Conclusions

From the above discussion it can be seen that the most common elements associated with gold ore deposits include iron, lead, arsenic,

bismuth, silver, copper and tellurium. Concentrates from individual deposits may show characteristic elements, while in some areas the different types of deposits may have qualitatively similar elements associated with the ore. Generally, however, there is a marked variation in the quantitative relationships of the trace elements from different deposits. With regard to the individual minerals associated with the ore, samples taken from different deposits may contain qualitatively and quantitatively similar trace elements. Certain elements may characterize an individual deposit or mining area and the concentration ratios between the elements may be constant in a given area. A particular element may indicate persistence with depth or grade of an ore deposit. Generally, the trace elements may indicate the type of mineralisation and conditions of deposition. The concentration and type of minor elements are affected by the temperature of the ore fluids especially.

C. THE MODE OF OCCURRENCE OF GOLD IN SULPHIDE MINERALS

The occurrence of gold in trace amounts in sulphides has been commented on by many workers and some have carried out experiments on synthetic minerals. For example, Maslenitzki (1944) prepared synthetic pyrite with varying concentrations of gold. Detailed study of the synthetic crystals under 1,200 times magnification revealed only a few isolated inclusions, which could not account for the high gold content in the pyrite. The high degree of dispersion of the gold was shown by the negligible amounts recovered by cyanidation and amalgamation, compared to the large residue of gold obtained as an amorphous brown powder on dissolution of the pyrite by strong acids. Heating of the polished sections of pyrite also illustrated the complete dispersion of the particles by causing the invisible particles to coalesce into layered aggregates of microscopic size. These segregations were very similar to those obtained by heating natural pyrite containing sub-microscopic gold.

The preparation of samples of pyrrhotite, containing 0.5% gold in the form of sub-microscopic particles or highly dispersed internal inclusions, revealed a degree of dispersion approaching the state of solid solution. Inclusions of what might have been gold sulphide were observed in the alloys. To investigate these further, a sulphide with the formula Au_2S_3 was prepared and found to be unstable at low temperatures.

In applying his results to gold inclusions in natural pyrite, Maslenitzki assumed that in the formation of ore deposits at a temperature of 400°C and with an elevated pressure of sulphur, melt solutions of iron sulphides could have formed with sulphides of other metals, including gold. With decrease in pressure and temperature, the crystallisation and separation of the pyrite from the other sulphides took place, as well as the decomposition of the gold sulphide. In the process of crystallisation of the pyrite, gold, as an element with a lattice of different size from that of the pyrite, was either retained inside the pyrite grains in the form of dispersed inclusions, or was squeezed out to the surface of the crystals and deposited as films. The conditions of cooling controlled which of the two possibilities occurred.

Kuranti (1941) also prepared synthetic auriferous iron sulphide. He found that up to 2000 ppm. gold could be uniformly distributed in the pyrite. The lattice constant of the pyrite decreased with increasing gold content, a fact proving solid solution of the gold in the pyrite.

The following are the natural sulphides in which gold is most commonly found, either as inclusions or as sub-microscopic particles: pyrite, pyrrhotite, arsenopyrite, chalcopyrite and galena. Sharwood (1911b) reported trace amounts of gold in pyrite from the Homestake Mine; 0.05 - 0.10 ozs/ton in pyrrhotite; and 0.9 - 1.7 ozs/ton in arsenopyrite. Since most of the gold in the arsenopyrite was amalgable, Sharwood suggested that it occurred in the free state. Uglow and Johnston (1923) found gold in galena, pyrite and arsenopyrite. Head (1935) and Blomfield, et al, (1936) observed minute particles of gold in pyrite. Head concluded that the flakes occurred in the crystallographic planes of the pyrite, while Blomfield and co-workers suggested that the gold had exsolved out of the pyrite during crystallisation.

Haycock (1937) found that most of the particles of gold in sulphides varied between 10 and 100 microns in size (i.e. they were visible), but that the sub-microscopic gold seemed to be in solid solution with the host. Gold tended to occur in sub-microscopic particles when it and the host mineral were deposited contemporaneously. Pyrite and arsenopyrite from the Dolphin East Lode, Fiji, contained uniformly distributed sub-microscopic gold, according to Stillwell and Edwards (1946). The authors were uncertain whether the gold occurred as dispersed particles of colloidal size or in true solid solution, but suggested a limited type of interstitial solid solution in which the solute gold atoms filled vacant spaces in the lattice. They found that invisible

gold occurred only in sulphides deposited in the early stages of mineralisation.

In contrast with the above evidence, Warren and Cummings (1937) found no proof of solid solution or eutectics between gold and other minerals. Similarly, Auger (1941) concluded that gold occurred as unevenly distributed atoms of free gold in the pyrite lattice. He based his conclusions on the inconsistent results obtained for gold on repeated arcings of the same specimen. It was also noted that pyrite which contained gold came from areas rich in visible gold, and, that in areas where no visible gold was present, the grade of ore had no effect on the spectrographic amounts of gold in the pyrite. Auger concluded that the gold was not in solid solution with the pyrite, but occurred in the native or combined state as isolated grains or fracture fillings within the pyrite crystals.

Summarising the above discussion, it can be seen that experimental work has shown gold to be capable of a very high degree of dispersion in pyrite, suggesting either solid solution of the gold with the sulphide or else its occurrence as minutely dispersed inclusions. In nature, sub-microscopic gold has been observed most commonly in pyrite, arsenopyrite, pyrrhotite, galena and chalcopyrite. The amount of gold contained in each mineral varies. The gold has been suggested by different authors to occur in the free state (i) as minute flakes exsolved out during crystallisation; (ii) in solid solution with the sulphides; (iii) as colloidal particles; (iv) as a uniformly distributed constituent in the sulphide; (v) as irregularly distributed isolated grains and minute veinlets of gold later than the host sulphide mineral.

D. THE GOLD-COPPER RATIO IN ORES

With regard to copper in native gold, Sharwood (1911b) noted that the amount of copper present in gold from the Homestake Mine was very small. The ratio of base metal (partly copper) to gold in free gold varied from a trace to 0.005, while the ratio of copper to gold in mill bars obtained by amalgamation was 0.018, and in the unrefined precipitate obtained by cyanidation, 0.240.

In the auriferous copper sulphides of the Santa Fe Mine, Mexico, Collins (1902) found that the cleaned copper concentrate contained 3.66 ozs. Au/ton Cu, compared with 7.04 ozs Au/ton Cu in the middlings concentrate of garnet and copper minerals. A variation in the

gold content of the ore with the grain size was also determined, the amount of gold increasing with decreasing grain size. The coarse fraction (3 - 8 mm.) contained 3.46 ozs Au/ton Cu, compared with 6.27 ozs in the fine fraction (less than 1 mm.)

A regional investigation of the variation in the gold-copper ratio in copper ores was carried out by Nye and Rayner (1940) for the Cloncurry copper deposits, Queensland. Both gold and silver existed in small amounts in the copper minerals and were probably distributed in the ores in a similar manner. The gold content varied from 1 to 8 dwts/ton Cu in the oxidised zone. The deposits seemed to be related to granitic intrusions and gold-bearing quartz veins occurred in the area. The results showed that gold and copper were similarly distributed throughout the area. The average gold-copper ratio was 0.0074 (ozs Au/% Cu). The highest ratios varied between 0.0083 and 0.0177 and were found in the southeast of the area. Gold was always associated with copper, but was richest in the southeast, where the largest copper producers were located. From an inspection of the maps given, it appeared as if the gold-bearing quartz veins were also concentrated in the southeast, though the authors did not comment on this. There appeared to be no regular arrangement of the gold-copper ratios, probably because of varying conditions of deposition and also because most of the ores examined were in the oxidized zone and had been subjected to varying degrees of erosion. Therefore, the gold and copper contents found did not necessarily reflect that of the primary ore. Any zonal arrangement of the ratios would probably have been evident only in the primary ore. However, the metal deposits did appear to be genetically related to an intrusive granite outcropping in the southeast of the area, where the ratios were highest. The ratios decreased to the west and northwest, with increasing distance from the granite.

It is impossible to draw any definite conclusions as regards the variation of gold and copper in ores from the above evidence, though it does seem likely that the gold-copper ratio might show similar variations to those in the gold-silver ratio in ore deposits, to be discussed in a later chapter.

E. SUMMARY AND CONCLUSIONS

From the above it appears that gold is essentially associated with the elements iron, lead, copper and arsenic. The common minerals of these elements - arsenopyrite, pyrite, pyrrhotite, chalcopyrite and

galena - are the most prevalent in gold ore deposits. The four elements, together with bismuth, silver and tellurium, are the most frequently occurring elemental associates of gold. Sub-microscopic gold has been detected most often in the above-mentioned minerals. In addition to the almost universal association between gold and these minerals and elements, it has been found that, in individual deposits, the gold is related to particular minerals and elements which indicate the conditions of deposition. In each metallogenetic district, however, all deposits show characteristic assemblages of the associated elements and minerals.

* * * * *

THE CHARACTERISTICS OF NATIVE GOLD IN ORE DEPOSITS

A. THE COMPOSITION OF NATIVE GOLD

(a) General

The composition of native gold varies markedly from grain to grain, sample to sample, and deposit to deposit. Generally, it contains silver, copper and some base metals in varying amounts. Rose and Newman (1937) gave the following normal composition for native gold: 99% Au + Ag; 0 - 1% Cu, Fe, Bi, Pb, Hg, Sn, Sb, Pd, Rh. Some natural alloys of gold have been briefly mentioned in the introduction. Rose and Newman (1937) listed the following additional alloys: rhodium-gold containing 34 - 43% Rh from Mexico; an alloy of 85.98% Au, 9.85% Pd and 4.17% Ag from Porpez; an amalgam of 38.39% Au, 5.00% Ag and 57.40% Hg from Choco, New Granada; an amalgam of 39.02 - 41.63% Au, and 60.98 - 58.37% Hg from Marilla, California; maldonite, an alloy of 64.5% Au and 35.5% Bi from Maldon, Victoria; an alloy of 85 - 90% Au and 8 - 9% Pd from Brazil.

Coated gold, found in the tailings lost on cyanidation of refractory ores, was analysed by Head (1935). It showed weak magnetic susceptibility, believed to be due to a film, or coating, or iron oxide, tarnishing the gold slightly. The coating appeared to be due to either mechanical adhesion of foreign material or impurities alloyed with the gold which had reacted with agencies in contact with the gold particles, thus forming the coating. Spectrographic analyses of the grains of gold revealed the following elements: Ag, Fe, Pb, Mn, Al and Ti. However, it was not certain whether these elements were in the gold itself or formed the coating. With reference to this analysis, it is interesting to note that Sharwood (1911a) recorded coated gold which was resistant to amalgamation. Chemical tests showed this coating to consist probably of Fe, Sb, Te, Bi and S. Head (1935) observed that the gold grains tarnished black in a 10% solution of Na_2S , indicating that the silver alloyed with the gold was concentrated at the surface of the grain.

One of the most important papers dealing with the spectrographic analysis of native gold is that by Crook (1939) who analysed several specimens of lode gold and placer nuggets. The elements present in the lode gold samples were Cu, Ag, Fe, Mo, Pb, Ni, V and Al. In the nuggets the following were found: Fe, Ag, Ni, Cu and Al. Three elements were common to all the samples analysed, viz. Cu, Ag, and Fe.

The detailed results are given in Table 4. Crook also examined polished sections of the specimens and reported the presence of grain boundary inclusions as well as minute inclusions in the gold crystals themselves. It was, therefore, concluded that silver, copper and iron were universally present in native gold, the first two elements probably occurring as metallic alloys, while the iron was present as iron sulphide, either alloyed with the gold or else present as non-metallic inclusions. The other elements present were also suggested to be constituents of non-metallic inclusions.

(b) Alaska

Nuggets from the Klondike were found by McConnel (1909) to be zoned in composition, the surfaces being richer in gold than the central zones. The analytical results of two of the nuggets were as follows:

	<u>% Ag</u>	<u>% Au</u>	<u>% Ag</u>	<u>% Au</u>
Centre	38.5	64.2	37.3	62.7
Surface	29.4	70.6	30.3	69.7

The increased gold content on the surface was explained by a surface refining action.

(c) Australia

Zemczuzny (1926) analysed three nuggets from Australia, one of which was zoned, with the following results:

	<u>Outer Zone</u>	<u>Middle Zone</u>	<u>Central Zone</u>
Au	79.28%	81.76%	79.78% 81.83%
Ag	17.31	17.75	17.40 17.71
Cu	tr	tr	tr tr
Insol.	0.78	0.16	1.53 0.25
Fe_2O_3 and			
Al_2O_3	0.54	-	- -

From his results, Zemczuzny formulated some interesting ideas on the origin of the nuggets. He visualized their being formed by crystallization in sedimentary layers from auriferous solutions. The mechanical deformation shown by some nuggets he explained by the disturbance of the layers during folding.

(d) Canada

Twenty-six samples of native gold from deposits in British Columbia were spectrographically analysed by Warren and Thompson (1944). The results confirmed Crook's conclusions that copper, silver and iron were always present in native gold. The elements found included Ag, Cu, Fe, Mn, V, Ti, Hg, Pb, Bi, Te, As, Sb, Zn, Cd, Sn, Pd and Pt. Elements such as Si, Ca, Al, Mg and Na were disregarded as they probably were derived from inclusions of gangue. Iron was found in gold from all deposits - even in those samples which contained no iron minerals - and was present in approximately equal quantities in all samples. Silver and copper showed similar distribution. Fourteen samples contained cadmium, but in only three of the fourteen was zinc found, despite the fact that the two elements are commonly associated in sphalerite. Gold from mines rich in bismuth and lead minerals and tellurides, showed bismuth, but no lead or tellurium. However, where tellurium was found in gold, either lead or bismuth was present, suggesting mechanical inclusions of lead or bismuth tellurides.

Because the samples chosen covered many types of deposits it was possible, from a study of the results, to conclude that the type of deposit might affect, but not control, the trace element content of the gold. Mercury, for example, was found in xenothermal, mesothermal, epithermal and pyrometasomatic deposits. Tin occurred in all types of deposits, though more frequently in those of high temperature. These two examples suggested that it was not the type of deposit, but the metallogenetic district which controlled the association between the gold and its trace elements. The association was probably chemical in nature rather than mechanical, and was probably due to a common source for the gold, mercury and tin. It also appeared that all the gold was deposited at approximately the same temperature irrespective of the type of deposit in which it occurred. Vanadium was detected in many different deposits and titanium in nearly all those examined. The presence of manganese was thought to be significant because of its importance in the solution of gold. With regard to the other minor elements, it appeared that, generally, they could be correlated with the elements in the minerals known to be present in the ore.

Warren and Thompson concluded from their results that metallogenetic provinces or districts were more important than the type

of deposit in determining the trace elements present in the gold, and that each metallogenetic province or district showed a characteristic assemblage of trace elements in gold.

Gold samples from veins in the Yellowknife district, Canada, were spectrographically analysed by Boyle (1961). Silver was present in variable amounts in all samples. Small amounts of Fe, Pb, Bi, As, Sb, Cu and Hg were also present and undoubtedly substituted in the metallic lattice of the mineral. Other elements detected, such as Ca, Al, Ti, Mg, B, Sr, V and Si, were probably present as contaminants, occurring in small inclusions of quartz, carbonate and sericite, as was commonly seen in polished sections of the gold. For the six samples analysed, the semi-quantitative results for the elements, assumed to be alloyed with the gold, were as follows:

Location	Ag	Fe	Pb	Bi	As	Sb	Cu	Hg
Early quartz lens, Con shear zone system	VS	W	M	M	tr	tr	tr	M
Early quartz vein, Negus Rycon shear zone system	VS	W	tr	tr	tr	W	tr	W
Early quartz lens, Giant shear zone system	S	tr	-	-	-	-	W	-
Late quartz-carbonate stringer, Campbell shear zone system	VS	W	tr	-	W	tr	tr	W
Ice lens, Giant Mine	M	W	-	-	-	-	tr	-
Ptarmigan veins	S	tr	W	-	-	-	tr	-

(VS : 10 - 100%; S : 1 - 10%; M : 0.1 - 1%; W : 0.01 - 0.1%; tr : 0.001 - 0.01%)

The qualitative results, given in Table 4, are very similar for all the samples.

In addition to their occurrence in the economic deposits, both gold and silver were found to be present in all the rocks in the district in amounts sufficient to produce the concentrations in the epigenetic deposits. Boyle, therefore, concluded that it was unnecessary to call upon magmatic hydrothermal solutions as a source of the two elements. Instead, the elements were suggested to be concentrated with sulphur, arsenic and antimony, in shear zones in greenstones and in quartz lenses

- 30 -

in sedimentary rocks by metamorphic processes and the dilatancy of various structures. The four generations of gold in the deposits were probably due to redistribution of the element within the deposit on four separate occasions.

(e) Congo

Van Aubel (1935) spectrographically examined native gold from eastern Urega, Belgian Congo and detected the presence of Ag and Fe as the major constituents; there was less Bi, Pb, Ti, Zn, Sn and Cu, and traces only of B, Mo, Sb and As.

(f) England

Russell (1929) analysed arborescent native gold found in calcite veins cutting Middle Devonian limestone in Devonshire, England. The gold was found only in fine-grained, buff calcite and not in associated coarse, brown calcite. The gold varied in colour from bright gold to pale silvery white, though the fineness was very high in all cases. Russell especially sought the platinum metals in his analysis, but did not detect them.

(g) Finland

Alluvial gold from the Ivalo River, Finnish Lapland was examined by Sundell (1936). In one nugget he found silver to be completely absent, the composition being 99.65% Au and 0.35% base metals. Another nugget consisted of 89.5% Au, 9.6% Ag and 0.89% Cu and Fe. Altogether the results of twenty assays were given, the gold contents varying from 77.1 to 99.6%.

Panned gold from the Lemmenjoki area, Finnish Lapland, and the Outokumpu Mine was described by Wilska (1952). The results of the qualitative analysis are given in Table 4; the quantitative results for five elements were as follows: Ag : 7.33 - 10.4%; Cu : .006 - .008%; Fe : .017 - .10%; Mn : .001 - .002%; Al : .08 - .10%. From his results Wilska concluded that silver was the main alloy constituent of the gold, the other elements occurring in trace amounts; platinum generally appeared to be rare in native gold; tellurium and bismuth were scarce in the gold from Finnish Lapland.

(h) Germany

Henrich (1926) gave the composition for native gold from the Rhein, Germany, as 93.4% Au and 0.069% Pt.

(i) Japan

Native gold from the Daikoku deposit, Chichibu Mine, Japan, was described by Miyazawa (1935). The gold occurred as small veinlets, fine granules, and linear or acicular masses, in sphalerite and arsenopyrite. Chemical analyses showed the composition to be 79.20% Au and 10.17% Ag, while the trace elements detected included Cu, Pb, Bi, Zn, Fe, Si, Al, Ca and Mg.

(j) Ruanda-Urundi

Gastelier, Peeters and Sorotchinsky (1947) dealt with the composition of six nuggets from the Nyongwe district, Ruanda-Urundi. The results for one well-zoned, nugget were as follows:

	% Au	% Ag	% Cu
Central Zone	92.04	7.91	0.5
Middle Zone	92.08	-	-
Outer Zone	92.51	-	-
Gold dust	92.23	7.57	0.4

The gold dust analysis represents a mean analysis for the whole nugget. From the results it could be seen that, as noted by McConnel (1909), there was an increase in the gold content from the centre outwards, in contrast to the previously quoted results of Zemczuzny (1926) and the observations of Head (1935), both of whom found an increase in silver outwards. In a second paper Gastelier and Sorotchinsky (1947) discussed eight nuggets, showing perfect crystal structure, from alluvial deposits in the Bumva region, Ruanda-Urundi. One of the nuggets was subjected to a complete analysis, the results of which were as follows: Au - 80.8%; Ag - 15.8%; Fe - 0.2%; Ca - 0.5%; Mg - 0.1%. The absence of copper was interesting in that it was assumed to be almost always present in native gold. As regards the origin of nuggets, the authors reached a conclusion similar to that of

Zemczuzny (1926) and suggested that the gold was precipitated from dilute aqueous solutions in an environment which did not restrict the formation of true crystals.

(k) Russia

Gold from the U.S.S.R. was reported by Nenadkewitch (1909) to have the following composition:

	<u>Au</u>	<u>Ag</u>	<u>Cu</u>	<u>Others</u>
Woiz	89.8%	9.45%	0.35%	Insol. 0.08%
Shilivo-	96.8	2.88	0.10	Bi - 0.13
Issetsk	94.9	2.84	0.11	Bi - 2.92

Fer'yanchich (1959) analysed gold nuggets and found several trace elements including Cu, Pb, Bi, Fe, Sb and Ag.

Pilipenko (1915) analysed gold and silver ores from various mines in the Western Altai, Russia. The following table gives the chemical compositions of several of these native ores:

	<u>% Au</u>	<u>Ag</u>	<u>Cu</u>	<u>Fe</u>	<u>Spec. Grav.</u>
(i)	71.02	28.86	nil	tr	15.96
(ii)	77.50	22.46	0.11	0.11	15.96
(iii)	61.88	38.05	tr	0.17	14.68
(iv)	61.85	38.23	tr	0.22	14.68

(i) and (ii) gold-silver ore from the Zmyeingorsky Mine.

(iii) and (iv) electrum from Zyryanovsky Mine.

Gold from the Baleisk Mine, Transbeikalia, was chemically analysed by Zvyagintsev and co-workers, (1938). The gold contained an average of 70% Au and 20% Ag. However, as pyrargyrite also occurred in the auriferous veins, the overall content of silver in the mined ore was much higher. Samples of gold were collected from various levels down to a depth of 120 metres and analysed. The results showed that neither the composition nor the microstructure of the gold changed with increasing depth.

(l) Southern Africa

Gold samples from Southern Africa have been analysed for variations in composition. Warren and Thompson (1944) obtained the following results for three samples:

	<u>Ag</u>	<u>Cu</u>	<u>Fe</u>	<u>V</u>	<u>Ti</u>	<u>Hg</u>
Matloui, Southern Rhodesia	S	F	F			F
Golden Valley, Southern Rhodesia	S	M	F			F
Barberton	S	F	F	F	F	F

S > .5% M : 0.1 - 0.5% F < .1%
Other elements sought, but not detected, were Pb, Bi, Te, As, Sb, Zn, Cd, Sn, Pd, Pt.

Liebenberg (1955) mentioned the presence of traces of mercury in visible gold from the Carbon Leader (Blyvooruitzicht Gold Mine) and the Kimberley reefs (Sub Nigle Gold Mine).

Steele and Carlton (1961) spectrographically analysed samples of visible gold from the Barberton district, their results being:

	<u>Ag</u>	<u>As</u>	<u>Cu</u>	<u>Fe</u>	<u>Mn</u>	<u>Ni</u>	<u>Pb</u>	<u>Sb</u>	<u>Si</u>	<u>Sn</u>
Barberton District	W	T	VW	W	T	VW	W	-	M	W
Trichardts Luck Mine	W	W	VW	W	T	VW	-	-	M	W
Lily Gold Mine	S	T	VW	W	W	VW	-	T	M	-

(Other elements sought : Al, B, Bi, Cd, Co, Cr, In, Mg, Mo, V, Zn)

S - strong; M - moderate; W - weak; VW - very weak; T - trace.

These results indicated the validity of Warren and Thompson's conclusion of a definite assemblage of trace elements for a particular metallogenetic province.

Eales (1961) has shown that the fineness of visible gold can vary markedly within a few microns.

(m) Conclusions

Table 4 is a qualitative summary of all the above-mentioned data. Silver is present in all the samples analysed and copper and iron in most of them. Lead, titanium, antimony, aluminium, mercury,

vanadium, manganese, bismuth, silicon, arsenic and tin are the most common trace elements. Generally nuggets and placer gold appear to have a far simpler composition than gold from veins, though Wilska's (1952) results for placer gold from Finnish Lapland do not conform with this generalization. The simpler composition may be due to the surface refining action to which placer gold is subjected. As regards individual metallogenetic zones, gold from Barberton district has a fairly uniform composition and appears to be similar to Southern Rhodesian gold and, possibly, to gold from the Belgian Congo. Californian gold is generally of simple composition, containing fewer trace elements than that from British Columbia and the Yukon. Boyle's results for gold from the different shear zone systems in the Yellowknife mining district are all remarkably similar. Too few analyses are available for Asian gold to draw any definite conclusions, though the results for gold from the Philipines, Japan and Berezovsk are similar. Wilska's results for gold from Finnish Lapland also indicate a characteristic trace element assemblage for the region. Therefore, it can be concluded that native gold is generally associated with a few characteristic elements. Silver, copper and iron are almost always present and it is only the presence of other minor elements which characterise gold from particular metallogenetic regions.

B. THE MODE OF OCCURRENCE OF TRACE ELEMENTS IN NATIVE GOLD

In order to understand the various suggested modes of occurrence of minor elements in native gold, it is necessary to briefly review the metallurgy of gold as regards the solubility of certain metals in gold. Hansen's (1958) is the most recent review of the subject and the data in Table 5 were compiled from his work. From the table it is evident that Ag, Cu, Ni, Pd and Pt can, under certain conditions, form a complete solid solution series with gold. Elements showing no, or very little, solid solubility in gold include As, Bi, Ir, Mo, Os, Pb, Rh, Ru, Sb, Si, Te and Tl. Al, Cd, Co, Cr, Fe, Ga, Hg, In, Mg, Mn, Sn, Ti, V, Zn and Zr are all capable of varying degrees of solubility in gold. Rose and Newman (1937) submitted data on ternary alloys of gold. Ag and Cu together form a solid solution series with Au; Cu together with one of the following elements: Sn, Bi, Sb, Al, Te and Pb, may also show partial solid solubility in gold. These Au-Cu - metal alloys tend to form gold-rich cores surrounded by copper-rich borders.

Zemczuzny (1926) found, contrary to metallurgical evidence, that gold and silver do not occur in nature in a continuous series of alloys. Pure gold can hold up to 30% silver. Mixtures containing 30 - 43% silver, i.e. electrum, are rare. The next series of natural alloys, containing 72 - 81% silver, is named kustelite. In pure silver less than 1% gold is present as an alloying constituent. The relatively low gold content in native silver has been attributed to the more ready reduction of gold salts in mixed solutions with silver salts. Experiments with solutions of AgCl and AuCl_3 showed that in 24 hours seven times more gold than silver was precipitated on reduction of the solution by silver.

Head (1935) and Sundell (1936) both made brief suggestions as to how the minor elements occurred in the gold. Head thought that the elements were either alloyed or mechanically included in the gold, while Sundell proposed that the base metals were present as minerals, not as alloy constituents.

Three possible modes of occurrence were suggested by Crook (1939), viz. alloy constituents; adhering gangue particles on the surface of the gold; and non-metallic inclusions in the gold. Dealing with the individual elements, it was postulated that silver and copper would probably precipitate under the same conditions as gold and, as the amounts of the two elements were known to affect the colour of the gold, it was considered reasonable to assume that the two elements were alloyed with the gold. However, in the case of iron, the metallic variety is very rare in nature and is difficult to produce by any igneous process or by electrolysis. Iron sulphide, on the other hand, is very common in gold vein deposits, and it appeared as if it and gold would precipitate under the same conditions. Therefore, Crook proposed that iron occurred in native gold as iron sulphide, either as an alloy in the gold molecule or as non-metallic inclusions on grain boundaries. Non-metallic inclusions were shown to be present in the gold by etching polished sections of the metal. However, all the structures observed under the microscope were due to pure metals or solid solutions; no intermediate compounds or eutectic alloys were observed.

Chemical combination and mechanical inclusions were discussed by Warren and Thompson (1944) as possible modes of occurrence of trace elements. Iron, silver and copper were reported in all gold samples examined, even those where minerals containing these elements were not found, and therefore, it was suggested that the three elements

occurred in chemical combination with the gold, not as mechanical inclusions. Since the cadmium content of the gold did not show any correlation with the zinc content, it appeared as if these two elements were also chemically combined with the gold and not present as mechanical inclusions of sphalerite. Tin and mercury were also thought to occur chemically in the gold, while bismuth, lead and tellurium were probably present as mechanical inclusions. The manner in which titanium, platinum, arsenic, vanadium and manganese were present was uncertain. Titanium was almost as common as iron, silver and copper, while manganese, arsenic and vanadium were often detected; platinum, however, occurred rarely. Because of the precautions taken to ensure the purity of the gold used, the authors suggested that all these elements were chemically combined with the gold. The other elements found, such as silicon, calcium, sodium, magnesium and aluminium, could generally be correlated with minerals known to be present in the ore.

Comparing the above-mentioned ideas with the available metallurgical evidence, several conclusions can be drawn, though it must be remembered that the metallurgical data usually deal with constituents present in much larger concentrations than trace amounts. With regard to copper, silver and iron, it seems feasible, from metallurgical evidence, to deduce that the three elements can occur in solid solution with the gold. Zemczuzny's evidence on silver and gold, however, seems to suggest that the elements tend to form alloys of definite composition. The proposal that iron occurs as iron sulphide seems unnecessary. Bismuth, lead and tellurium all impart brittleness to gold when present in small amounts and only form alloys when they occur in relatively large amounts. These observations seem to indicate mechanical combination of these elements with the gold. Similarly, the experimental metallurgical data do not deny Warren and Thompson's other conclusions as regards modes of occurrence, except for As, though it must be mentioned that aluminium, magnesium and silicon may alloy with gold under certain conditions, suggesting that they need not necessarily be present in gold as gangue inclusions.

C. SUMMARY AND CONCLUSIONS

From the evidence reviewed, it is evident that silver, copper and iron are almost always present in free gold, from both vein and placer deposits. Other common trace elements include lead, titanium, antimony, aluminium, mercury, vanadium, manganese, bismuth, silicon, arsenic and tin. The modes of occurrence of the elements in

Element	Maximum solid solubility (atomic %)	Temperature °C
Ag	100	
Al	15.5	530
As	0.2	611
Bi	0.07	900
Cd	32.5	612
Co	22	1000
Cr	18	1150
Cu	100	
Fe	56.5	1168
Ga	25	351
Hg	19.5	420
In	12.64	700
Ir	very small	
Mg	25	827
Mn	32	960
Mo	1.25	1054
Ni	100	820
Os	negligible	
Pb	negligible	
Pd	100	
Pt	100	1260
Rh	0.56	900
Ru	negligible	
Sb	1.12	600
Si	limited	
Sn	6.8	498
Te	negligible	
Ti	8.5	1000
Tl	0.9	800
V	17.5	970
Zn	31	642
Zr	7.25	1065

Table 5 : Maximum Solubility of Various Metals
in Gold (after Hansen, 1958)

the gold crystals are uncertain. Silver, copper, iron and nickel are all capable of complete solid solution with gold, as shown by metallurgical evidence, and these elements probably occur in the gold lattice. Tin is capable of partial solid solution with gold, while lead, aluminium, antimony and bismuth can also enter into the gold lattice, provided copper is present. Lead and bismuth, when occurring with tellurium in gold, possibly take the form of mechanical inclusions. However, the widespread occurrence of lead, in particular, seems to suggest some chemical combination with the gold. The manner in which manganese, arsenic, vanadium and titanium occur is not known, though their common association with gold seems to indicate that they are chemically combined with it, despite the negligible degree of solubility of arsenic in gold.

All native gold appears to have a qualitatively similar trace element assemblage, though placer gold is generally simpler in composition than vein gold. The minor elements found in gold, excluding silver, copper and iron, may be characteristic for a particular metallogenetic province or district.

* * * * *

THE FINENESS OF GOLD ORES

A. INTRODUCTION

Gold fineness has been defined by Fisher (1945) as the ratio $Au / (Au + Ag) \times 1000$. This definition eliminated the affect of base metals, a factor which previous definitions had not considered. Several workers, instead of studying variation in fineness, have considered the variations in the gold-silver ratio, either of the ore or of mine bullion.

Studies of the fineness of gold reported in the literature illustrate the remarkable variation in the results from deposit to deposit, from level to level within a single deposit, and from grain to grain. Many authors - including Russel (1929), Mather (1937), Edwards (1958), Eales (1961) - have remarked on the difference in colour indicating variation in fineness between grains from a single sample, and Eales, (1961) drew up a colour scale for estimating the fineness quantitatively.

Fineness has also been found to vary with the type of host-rock. Lincoln (1911) reported that gold in basic igneous rocks was 245 fine; that in intermediate igneous rocks 451 fine; while gold in acid rocks had an average fineness of 979. Polinard (1944) showed that the gold and silver contents of an auriferous quartzite from the Lulua Basin, Katanga, varied independently of each other, and that the gold content seemed to be related to the degree of metamorphism of the country rock. Silica introduced after the mechanical deformation of the rock acted as a medium for the transport of the gold. Ward (1958) noted that in the Western Australian gold mines, the ore bodies were all genetically related to albite porphyry intrusives and were characterized by a simple mineral association and by a high gold:silver ratio which was always greater than 9:1. For the ores of the Yellowknife district, Boyle (1961) found that deposits in greenstones had a gold:silver ratio of 5:1, while those occurring in quartz lenses in the sediments had a ratio of 3.5:1.

The fineness of individual grains varies within the grains themselves. For example, Head (1935) reported gold grains which were finer in the centre than on the surface. Eales (1961) observed the reverse relationship, viz. silver-rich cores with gold-rich exteriors.

Gold from placer deposits, in particular, shows marked variations in fineness values. Gold of very high fineness has been reported from such occurrences. Smith (1913) found that placer gold from the Fairbanks district, Alaska, varied in fineness from 792.5 to 950, with a mean of 880. In a later paper, Smith (1941) recorded that the fineness of placer gold from deposits throughout Alaska varied from 565 to 970; most of the deposits contained gold of 850 to 899 fineness, while very few had gold less than 800 fine. Hite (1933) and Sundell (1936) both commented on the fineness of very fine-grained placer gold. Hite found that flour gold from the Snake River, Idaho, had a fineness of 951 - 954, while the gold from the Ivalojoki placers, Finland, was reported by Sundell to be 930 - 961 fine, most of the values lying between 940 and 944.

Lode gold usually has a lower fineness than placer gold. Smith (1913) for example, gave the fineness of the lode gold from which the Fairbanks placers were derived, as varying between 780.5 and 843, with a mean value of 817. The following is a table quoted by Smith (after Lindgren) giving the fineness of lode gold from Californian quartz veins:

	<u>Fineness Range</u>	<u>Mean Fineness</u>
Plumas County	627 - 850	738
Sierra County	622 - 883	752
Nevada County	645 - 890	768
Placer County	580 - 921	750
Eldorado County	570 - 901	735
Calaveras County	627 - 975	801

However, gold of very high fineness has also been reported from gold veins. Maclare (1908) mentioned gold 999.1 fine from the Great Boulder Mine, Kalgoorlie, 999 fine from Cripple Creek, Arizona, and 997 fine from Mount Morgan, Queensland. Sharwood (1911a) found that free gold associated with goldfieldite from Goldfield, Nevada, was 996 fine and, from other observations, he concluded that exceptionally fine gold was normally derived from telluride minerals. Russell (1929) commented on very fine, arborescent gold from a calcite vein in Devonshire, England. The gold varied in colour from silvery-white to rich-gold, but the fineness was generally high, the values being as follows:

	<u>bright-rich gold</u>	<u>silvery-white gold</u>	<u>silvery-white gold</u>
% gold	98.11	91.59	92.53
% silver	1.89	8.41	7.47

Mention must be made of the variations in silver content of gold from reefs in the Witwatersrand Goldfield. Lane-Carter (1902) found that the silver content of the ore on one mine varied from 9 to 19%. Dures (1913) reported that the silver content of the ore from different mines varied between 8.5 and 14.5%. Prentice (1939-40) calculated from bullion data and various empirical corrections, the gold, silver and pyrite content of the ores sent to the reduction works on the Witwatersrand, arguing that this should represent the ore in situ underground. The average silver content on this basis was 9.64%. The mean silver contents for the various reefs were determined as follows: Main Reef Leader - 8.0%; Upper Leaders - 8.6%; South Reef - 7.8%; Main Reef - 9.5%; Composite Reef - 7.8%; Bird Reef - 8.7%. Richards and Rubidge (1950), however, found the average silver contents for the individual reefs to be: Leader Reef - 7.9%; South Reef - 8.5%; Main Reef - 9.65%; Bird Reef - 9.00%; Kimberley Reefs - 13.7%. Finally, both Frankel (1939) and Richardson (1939-40) reported values for the fineness of gold from the Black Reef. Frankel found free gold from the Black Reef in the New Machavie Mine to contain 7.9% silver while Richardson reported an average silver content for the gold of 13%.

B. VARIATIONS IN THE GOLD-SILVER RATIO OF GOLD ORES

(a) Alluvial Gold Deposits

It has been noted that there generally is an increase in the fineness of alluvial gold downstream from its source and that the increase is possibly due to the dissolution of silver as the gold travels further from the source. McConnel's (1909) results illustrating the enrichment of gold at the surface of nuggets from the Klondyke, have already been quoted. It was concluded that the enrichment was due to a surface refining action. Smith (1913) suggested that the variations were probably due to the addition of gold from different sources. Fisher (1934) amplified this idea, proposing that the increase in fineness downstream in the Morobe Goldfield, New Guinea, was mainly due to the gravels' being supplied with richer gold downstream. He also favoured an electrolytic-corrosion process involving the removal

of silver from the gold-silver alloy and the redeposition of the associated gold on the surface of the nuggets and flakes as thin films of fine gold. Smith argued that it was possible for the fineness of gold particles, not being transported, to increase purely as a result of surface weathering processes. In this regard, Knopff (1913) quoted an example at Mount Morgan where unoxidized gold was 570 fine, while that in the oxidized zone was 998 fine. He thought that the refining in the oxidized zone was due to the solution and redeposition of gold. He argued that, when calculating the refining action of transportation on gold, the enrichment of the lode gold in the oxidized zone should be considered.

Fineness variations in placer gold from the Barkerville area, British Columbia, were considered by Uglow and Johnston (1923) to be due to differences in the original character of the vein gold. They concluded that there was no evidence to suggest that placer gold is generally finer than lode gold. The placer gold in the area varied from 775 to 950 fine, compared with finenesses varying from 850 to 910 for the lode gold.

Fisher (1945) concluded from a study of the Morobe Goldfield that the variations in fineness of alluvial gold were mainly due to the calculation of fineness from bullion returns, as well as to variations in the methods of ore treatment and the presence of silver minerals in the ore. The increase in fineness downstream was suggested to be due to a surface refining action involving the leaching of either silver or gold and silver. The rate of refining appeared to be dependant on the size of the particles, being greatest for the smaller particles. From a review of the data on the fineness of gold in deposits throughout the world, Fisher concluded that alluvial gold had a higher fineness than the average vein gold and that its fineness increased downstream due to a surface refining action as the size of the grains decreased. Colin (1946) arrived at the same conclusions after a study of gold from the Macequece field, Madagascar.

Hargraves (1961) found that gold from the Ventersdorp Contact Reef and the Black Reef, in the Witwatersrand Basin, had a similar, or higher, silver content than that of the gold ore in the reefs from which they were believed to have been derived. If the two reefs represent placer deposits, then it could be expected that the gold would be finer than that in the parent deposit.

From the above discussion, it may be concluded that alluvial gold is generally accepted to be finer than the vein gold from which it

is derived. The increase in fineness is due to a surface refining action, involving the removal of silver, or of gold and silver. The fineness of gold in placer deposits generally increases downstream with distance travelled. This variation is partly due to a surface refining action, and partly to the addition of new gold from different sources.

(b) Lode Gold Deposits

(i) Vertical Variation in Fineness

In lode gold deposits, the fineness has been found to vary remarkably from grain to grain, stope to stope, and level to level, but there is a general systematic change with some variable physical factor.

Many workers have reported a change in fineness with increasing depth of the ore vein. Don (1897) gave the following examples:

1. Northern Gold Field, Otago, New Zealand:

Fineness of surface gold	-	906.45
Fineness of deeper gold	-	902.4
2. Macetown District, Otago, New Zealand:

Fineness of surface gold	-	946.02
Fineness of gold at 1000'	-	942.93
3. Dart River, Victoria, Australia:

Fineness of surface gold	-	935.48
Fineness of unoxidized gold	-	909.84
4. Bendigo, Victoria, Australia:

Fineness of surface gold	-	945.35
Fineness of gold from 1200' - 3000'	-	935.8

The results showed that, in general, in the same district, the fineness of gold is greater near the surface than at depth. It also appeared that the surface gold was more uniform in quality. However, it must be remembered that Don's results compared gold from the oxidized and unoxidized zones and it has already been mentioned that gold tends to be refined in the oxidized zone. Therefore, the results do not necessarily indicate any primary variation in the composition of the gold. Both Fisher (1945) and Colin (1946) pointed out that oxidized gold is always richer than the primary ore and several other authors

have noted a decrease in fineness on passing from the oxidized into the sulphide zone. Contrary to these observations, Sharwood (1911b) reported a greater silver content in the oxidized free gold of the Homestake Mine than in the unoxidized gold. He suggested this increase as probably being due to later enrichment in silver.

Macgregor (1928) observed a gradual decrease from the surface downwards, in the fineness of the ore of the Lonely Mine, Southern Rhodesia. Above the 21st. level, the average fineness was 958; at the 21st. level 951; at the 22nd. level 934; at the 23rd. level 930; and at the deeper levels 920, 902 and 891. The change in fineness seemed to be related to a zonal change in the character of the ore body below the 21st. level. From surface to the 21st. level, conditions of mineralization appeared to have been uniform; below the 21st. level the drop in fineness heralded the approach of zonal change which was observed where the fineness dropped below 900 and copper, lead and zinc sulphides appeared in significant quantities.

Macgregor calculated the fineness from the annual production records of the mine and Bruce (1943) adopted a similar procedure when studying the change in the gold-silver ratio of the ore of some of the deeper Canadian gold mines. These data on the change in composition of the bullion of each mine do not give a true picture of the metal content of the ore. Nevertheless, Bruce tentatively concluded that the gold-silver ratios for some deposits decreased with depth; that the ratio was different for different types of wall-rock on the same level; and that the silver content of the ore was less variable than the gold content. A further example of a decreasing gold-silver ratio with depth, is that given by Fisher for the ore of the Edie Lode, Morobe Goldfield. His results were as follows:

<u>Depth Below Surface</u>	<u>Gold:Silver</u>
0 - 150'	56:1
80 - 235'	42:1
135 - 290'	35:1
270 - 425'	27:1

However, Fisher pointed out that there was strong evidence for the secondary deposition of the gold and that secondary enrichment of low fineness ores with redeposition of gold and silver resulted in a similar grade of ore to that originally deposited. In other words, Fisher argued that the decrease in the ratio with depth was due to secondary

enrichment in the oxidized zone, decreasing with depth to the unoxidized zone.

Following Fisher's ideas, some workers noted a decrease in the fineness of gold with increasing depth until the fineness became constant. Sharwood (1911b) studied the variation in the gold-silver ratio of the ore from the Homestake Mine. Earlier Emmons (quoted by Sharwood) had noted an increase in the percentage silver bullion produced from 1880 to 1900, a fact which he partly explained by suggesting variability in the gold-silver ratio of different grains of native gold, or in different ore-bodies. The following table gives the mean values for the gold-silver ratio of the ore on each vertical level, as determined from Sharwood's data.

	<u>Au °/oo</u>	<u>Ag °/oo</u>	<u>Base Metal °/oo</u>	<u>Ag:Au</u>
surface workings	824.5	174.1	1.4	.211
400, 500, 600 levels	833.2	162.6	4.2	.195
700, 800, 900 levels	837.8	159.5	2.7	.191
1000 and deeper				
levels	832.7	161.6	5.7	.194

The results indicated an increase in the proportion of silver to gold down to the 400 feet level, but from there onwards the ratio remained approximately constant. The variation in the upper levels was suggested to be due to differential leaching by surface waters, or else to differences in the conditions of original deposition of the gold on successive horizons. Sharwood concluded that the increase in the silver content in the bullion could best be explained by changes in the metallurgical recovery methods employed.

Mackay (1944) studied the gold-silver ratios of ores from the Lupa Goldfield, Tanganyika, and from deposits in Nigeria. From his results he proposed that, generally, the gold-silver ratio became constant with increasing depth as the primary zone of mineralization was reached. He found that the gold in the oxidized zone was much purer than the primary gold and suggested that this was due to a secondary enrichment process in which the gold deposited had less silver than the primary gold. This was contrary to Fisher's (1945) ideas. Mackay also observed that the enriched gold was easily amalgamable while the primary gold was recovered only by cyanidation. He put forward the idea that, by comparing the silver-gold ratios of the gold recovered by amalgamation and cyanidation, the degree of

secondary enrichment could be determined. Mills (1954) concluded that the high purity of the gold in the O'Brien Mine, Quebec, from surface to the 500 feet level was probably due to supergene enrichment.

Increases in the fineness of primary gold ores with depth have been reported by several investigators. Collins (1902) found that the fineness of most of the gold ores in Gilpin Co., Colorado, remained constant with depth. The fineness in one vein, however, did increase with depth. Fisher (1945) argued that the fineness should increase with depth for primary gold since gold is less soluble than silver and precipitates out from the ore fluids first. From a review of gold deposits throughout the world, he substantiated this argument and concluded that the fineness of the gold generally increased with depth of deposition i.e., with high temperature and pressure. The fineness of the primary gold was, therefore, characteristic of the type of ore. For example, hypothermal gold was always greater than 800 fine, mesothermal gold varied from 750 - 900 fine, but could be purer, while epithermal gold ranged from 500 - 800 fine. Also, under any given set of conditions, gold fineness tended to be constant, especially in deposits genetically connected. Colin (1946) reached similar conclusions from his study of the epithermal and mesothermal deposits in the Macequece field, Madagascar. The fineness of epithermal gold varied between 600 and 780 and that of the mesothermal gold between 700 and 900. In a series of parallel reefs connected by stringers and veins the fineness was found to increase from 768 in the uppermost reef to 916 in the lowest reef.

From bullion assays and mine records, Mills (1954) found a systematic vertical zoning in the fineness of the ore of the O'Brien Mine, Quebec. From surface to 500 feet the fineness was 900 - 910, the high value probably being due to supergene enrichment. From 500 to 1200 feet the fineness increased from 860 to 920, and below 1200 feet it remained constant at 920. Bruce (1943) also studied the gold-silver ratio of the ore of the O'Brien Mine but found a decrease in the purity of the gold with increasing depth. Edwards (1958) reported an increase in the fineness of the ore of the Maude and Yellow Girl mines with increasing depth and sulphide content of the ore. The free gold had an average fineness of 725.

Hargraves (1961) found that the silver content of the gold ores in the Witwatersrand reefs seemed to be a function of elevation, reefs in shallow areas having a greater silver content than reefs in

the deeper areas. For individual reefs he found that the Main Reef group generally contained less silver than the stratigraphically higher Kimberley and Bird Reef groups. Under the modified placer theory for the origin of the gold, these observations implied considerable redistribution of silver, relative to gold, during the solution stage. The data are insufficient to suggest whether redistribution of silver could have occurred between reefs, or only within the individual reefs.

In conclusion, it is apparent that oxidized gold is much finer than primary gold and that there is generally a decrease in fineness as the ore passes from the oxide to the sulphide zone. With regard to the primary ore, several authors have reported a decrease in fineness with increasing depth of the deposit, up to a certain depth below which the fineness value remains constant. The decrease in value is thought to be due to the differences in the conditions of deposition on successive horizons. Contrary to the above, some workers have reported an increase in fineness with depth and have correlated the increase with increasing temperature and pressure at the time of deposition. Gold fineness is thus believed to be characteristic of the type of ore deposit.

(ii) Lateral Variations in the Fineness

The fineness of gold has also been found to vary laterally along a vein or over a whole region. Collins (1902) showed that the gold-silver ratio for the gold ores of Gilpin Co., Colorado, varied as follows: a central oval area (five square miles) of high gold values was surrounded by a ring of gold-silver ores, which in turn was enclosed by an outer ring of silver-rich ores. Sharwood (1911b) gave the following table of average bullion assays for mines ranging from north to south along the Homestake lode to illustrate the horizontal variation in fineness of the ores:

Mine	Au %/oo	Ag %/oo	Base metal %/oo	Ag:Au
Homestake	820	170	10	0.207
Highland	830	155	15	0.187
Terra	825	160	15	0.192
Deadwood	850	140	10	0.165
De Smet	820	170	10	0.207

The fineness of Witwatersrand gold increases from east to west as follows: 865.8, 884.0, 870.6, 926.0, 912.0, 924.0 and 970.0. The direction of increase is contrary to what would be

expected if the gold were of placer origin, as the feeder streams generally seem to have flowed from the northwest. Lawn (1924) found that in individual mines on the Rand, ore from the west of the mine tended to be low in silver. Samples from Government Areas, New State Areas, Van Ryn Deep and Langlaagte Estate gold mines, all showed similar variations in the silver content of the gold. The silver content varied from stope to stope and there was a tendency for it to be correlated with the grade of the ore. However, Lawn considered that locality was the most important factor in determining the silver content of the gold. Prentice (1939-40) also concluded that reefs on the Witwatersrand varied from east to west, with the ore of the western mines containing less silver than that of the eastern mines. He suggested that the variation was due to a higher percentage of free gold in the western mines. The coarser, free gold, was found to contain less silver than the non-amalgamable fine-grained gold.

(iii) Grain Size and Variation in Fineness

The fineness of gold has been found to vary systematically with the size of the grains. This variation may be correlated with observed variation in fineness between amalgamable and non-amalgamable gold, the former being generally coarser than the latter.

In 1902, Collins reported that in the ores of Gilpin Co., the coarser concentrates carried less silver than the finer concentrates. This observation has been confirmed subsequently in other deposits, though in placer accumulations it is generally the finer-grained gold which is the purest. For example, Hite (1933) reported flour gold 954 fine; Sundell (1936) found very fine-grained alluvial gold to be up to 961 fine; Frankel (1939) determined fine-grained gold from the Black Reef to be 921 fine. Sharwood (1911b) found that there was a decrease in the fineness of free gold from the Homestake Mine with decreasing grain size, as the following table shows:

	Grain Size	Silver:Gold	Equivalent Fineness
Surface workings	Coarse	0.203	831
	Medium	0.215	823
	Fine	0.215	823
400, 500 and 600 levels	Coarse	0.178	849
	+ 50 mesh	0.196	836
	-50 + 100 mesh	0.197	835
	-100 mesh	0.210	826
700, 800 and 900 levels	Coarse	0.177	849
	+ 100 mesh	0.193	838
	- 100 mesh	0.202	832
1000 and deeper levels	Coarse	0.189	841
	+ 100 mesh	0.191	839
	- 100 mesh	0.202	832

On the Witwatersrand, Prentice (1939-40) observed that the coarser grains were purer than the finer particles, the silver content of the free, amalgamable gold varying from 7 to 8.5%, while non-amalgamable gold contained from 8.5 to 13% silver. Mackay (1944) noted that, for the ores of Tanganyikan and Nigerian goldfields, the ratio of gold to silver was highest in amalgamable gold. The purer gold was secondarily enriched and much coarser than the primary gold.

However, the opposite relationship has also been reported. Mills (1954) found that in the O'Brien Mine, the fineness increased with increasing depth in the primary zone of mineralization until a constant value was reached, but the particle size decreased with depth. In the Olympus Mine, Southern Rhodesia, Eales (1961) showed that the purer gold occurred in small discrete grains, while impure gold occurred in much larger grains, associated with chalcopyrite. The ratio of amalgamable gold to non-amalgamable gold increased with fineness, indicating that the smaller particles were more susceptible to amalgamation than the larger ones. Similarly in the Lonely Mine, Eales found that, in the upper levels, the gold occurred in discrete grains less than five microns in size, with a fineness of 940, while at depth

the gold was much coarser-grained and pale yellow in colour, indicating a high silver content.

It is, therefore, apparent from the above examples that while a correlation between grain size and fineness might exist for a particular deposit, it is not universally applicable to all deposits. In some deposits the gold fineness increases with decreasing particle size, while in others it decreases with decreasing particle size.

(iv) Grade of Ore and Variation in Fineness

It is to be expected that there might be a correlation between fineness and grade of ore. On the Witwatersrand, most workers have observed that the silver content of the ore decreases with increasing grade. Lawn (1924), for example, noted that, generally, in Rand mines, low silver values were associated with high-grade ore, though he mentioned that on Government Areas the lowest silver content of the ore, 6.5%, was obtained in a low-grade stope, while the highest silver content, 14.5%, was found in a high-grade stope. Prentice (1939-40) confirmed Lawn's observations, noting that the silver decreased as the gold content increased. For the ore from the Black Reef, the percentage silver was found by Richardson (1939-40) to decrease from 15.9 to 11.6% with increasing grade. Richards and Rubidge (1950) observed that for all reefs of a grade lower than 10 dwts./ton the silver content tended to rise with a lowering of the grade.

In gold vein deposits, similar variations between fineness and grade have been observed. Mackay (1944) noted that in the Lupa Gold-field, as the grade of ore decreased with depth, so did the gold-silver ratio of the ore.

In Southern Rhodesia, Macgregor (1928) pointed out that, at the Lonely Mine, the fineness of the gold increased with the grade of ore. Eales (1960, 1961) confirmed this and recorded similar variations in twenty other deposits, including the Olympus, Horn and Turk Mines. In the Olympus Mine it was calculated that an increase of 1 dwt./ton in grade was accompanied by an increase of 30 to 35 % in fineness, a relationship which seemed to hold for most other deposits. Mineralographic study of the Olympus ore showed no supergene enrichment, indicating that the correlation between grade and fineness referred to the hypogene ore. The fineness was calculated from bullion data and also from channel samples taken along the shoots. Both methods showed similar variations, though those from the bullion data were

much less marked. In the Turk Mine, the very rich samples contained gold 830 fine, while the low-grade ore was less than 600 fine. Patches of gold with high fineness, were, however, fairly common in low-grade ores, due probably to the metal representing small amounts of late, pure gold. Lenses of silver-rich gold in high-grade sections were rare.

Edwards (1958) observed similar localized patches in the Maude and Yellow Girl Mine where assays along the reefs showed very high silver values, in excess of the gold content, probably resulting from the presence of silver in independent minerals. In contrast, small pockets and shoots of very fine gold (finenesses of up to a 1000 were recorded) occurred sporadically on all levels of the mine, generally in silver-poor sections, though high quality gold was also located in the silver-rich sections. The gold-silver ratio of the ore varied from 10:1 to 1:100 in individual assays, but certain sections of the vein tended to be either silver-rich or silver-poor, thus indicating that gold and silver were introduced into the vein to some degree independently of each other. Despite the variations in the gold-silver ratio, the overall fineness of the gold in all sections remained between 700 and 750.

Eales explained the relationship between the average grade of ore and the purity of gold by suggesting that there was an increase in the purity from the earlier to the later stages, and that the rate of precipitation tended to increase as the later minerals settled out. Supporting these proposals, he found (Eales, 1960) that pyrrhotite generally occurred with gold of low fineness; pyrite and arsenopyrite with gold of varying fineness, depending on their relative ages; sphalerite and chalcopyrite with silver-rich gold. Galena seemed to mark the stage in the paragenetic sequence after which the fineness of gold being deposited began to rise. Therefore the associated gold varied in fineness with the period of deposition; late minerals such as tellurides, native antimony and bismuth minerals were generally accompanied by gold of very high fineness. With regard to the last observation, it is of interest to note that Shcherbina (1956) postulated, from theoretical considerations, that, whereas gold predominated in tellurides, silver was dominant in selenide ores. Fisher (1945) also concluded that gold had a greater affinity than silver for tellurium. Eales's idea of silver-rich early gold is contrary to Fisher's (1945) conclusion that the earlier the period of deposition, the higher the tenor of the gold.

(v) Fineness Variations and the Period and Conditions of Deposition

The above section mentioned briefly ideas on the effect of conditions of deposition on gold fineness. With regard to primary gold, many workers favour the idea that gold deposited early in the paragenetic sequence is purer than later gold. This is in accord with the generally accepted views on ore deposition. The conclusions of Fisher (1945) and Colin (1946) that hypothermal gold is finer than mesothermal gold which, in turn, is finer than epithermal gold, have previously been quoted. Shcherbina (1956) supported the contention that older deposits are enriched in gold relative to silver. However, contrary to the accepted view, Eales (1960, 1961) suggested that the composition of gold precipitated during ore deposition changed from silver-rich in the early stages to silver-poor in the late stages.

Temperature and/or pressure have been put forward by most writers as the factors of importance in controlling the composition of the gold. Fisher (1945) decided that the temperature and pressure prevailing at the time of deposition in a particular place, were the dominant factors, though the greater insolubility of gold over silver, might also have affected the purity. He found that at depth with high temperatures and pressures, silver did not alloy with gold, but formed native silver or argentiferous minerals. Shcherbina (1956) also observed that gold was enriched in high temperature deposits at depth; while silver concentrated at medium depths and near surface. However, he was of the opinion that the vapour pressure of the two elements was the controlling factor. Edwards (1958) assumed that the pressure remained constant and proposed that temperature was probably more important. Eales (1960) decided that temperature was not of paramount importance in determining the composition of the gold, though it undoubtedly had some effect.

Perhaps, the most important and obvious factor in determining the fineness of native gold, is the amount of silver available at the time of deposition. Edwards (1958) argued that the concentrations of silver and other elements, with which the silver could combine instead of alloying with the gold, were of fundamental importance. Provided that there was an excess of silver available, a factor such as temperature probably controlled the amount of silver alloyed with the gold. If this were not so, the gold and silver content of the ore at any given point along the vein, would vary sympathetically, instead of

antipathetically, as has been observed. Both Eales (1960) and Fisher (1945) argued that the ore fluids would have to be basically silver-poor for the silver concentration to affect the fineness of gold. Fisher pointed out that concentration of silver, as given by the silver-gold ratio, had little effect on the fineness, except where insufficient silver was present to alloy with the gold under the prevailing physical conditions. Eales suggested that the change from gold of low fineness to that of high fineness, with increasing metallization, seemed to depend on the availability of silver, provided the ores were basically silver-poor.

Other factors considered to affect the fineness of gold include the chemical environment at the time of deposition, which Eales proposed would differ fundamentally in different depth zones, though he did mention that selective precipitation of gold and silver by different minerals cannot explain the observed variations in composition. Shcherbina indicated that the type of ore fluids could affect the composition, and showed that deposits formed from more alkaline hydrothermal solutions were richer in gold than in silver. He also showed that the regional metallogenetic features affected the silver-gold ratio of an individual deposit.

The degree of permeability was considered by Eales to be important in controlling the observed variations between fineness, tenor of the ore and the paragenesis of the gold. If ore shoots formed where a high degree of permeability existed up to the final stages of ore deposition, then the gold in such richer sections would have been late in the paragenetic sequence, and therefore, from the results obtained, relatively pure. However, where portions of the channelways became blocked by the deposition of quartz and sulphides, the late stage minerals would have been deposited in small amounts. In other words, in such areas the concentration of the gold would have been low and the gold present would have been rich in silver. Therefore, gold of low fineness would have been characteristic of low-grade ores.

De Haan (1943) attempted to explain the variations in the gold-silver ratios of the gold and silver veins in Tertiary volcanic rocks in Sumatra. These veins were very rich in silver, the gold-silver ratio varying from 1:1 to 1:2300 in different deposits. The variations between individual veins was explained by a process of fractional distillation from a parent magma. As the magma cooled solutions of differing composition distilled off and rose up the available fractures at different times. Variations along a single vein were suggested to be due to

tectonic movement causing sub-differentiation of the ore fluid.

It is, perhaps, pertinent to discuss briefly the affect of the conditions of deposition on the fineness of secondary gold. Generally, supergene gold is accepted to be enriched in gold relative to silver. Knopff (1913), Mackay (1944), Fisher (1945), Colin (1946) and others have all observed that supergene gold was much finer than the primary gold from which it was derived, though Fisher found that in the Edie Lode, Morobe Goldfield, secondary enrichment of low fineness ores with redeposition of gold and silver resulted in a similar grade of ore to that originally deposited. The cause of enrichment was suggested by Mackay to be differential solution of the silver relative to the gold, as in alluvial processes. He stated that secondary enrichment was most marked where large amounts of copper were present, indicating some chemical relationship between copper and gold enrichment. Fisher (1945) pointed out that a manganeseiferous environment was necessary for secondary enrichment. Manganese could, under certain conditions, cause the liberation of nascent chlorine, which would dissolve the gold. Shcherbina (1956) argued that, in surface processes, silver was more easily chemically transported than gold, a conclusion supported by the higher ratio of silver to gold in sea-water than in the lithosphere.

Summarizing the above discussion, it can be seen that the concentration of silver in the ore fluids and the temperature and pressure conditions prevailing at the time of ore deposition, are generally accepted as being the most important factors in determining the fineness of primary gold. Most writers consider that the early gold deposited is finer than the later gold, in accordance with the accepted paragenetic sequence of ore minerals. However, evidence has been put forward that early gold is silver-rich and that the proportion of silver alloyed with the gold decreases with increasing rate of metallization, as the later gold is deposited. In a particular deposit, uniformity in composition of the gold indicates uniformity in conditions of deposition or age.

(c) Practical Applications of the Variations in Gold Fineness

The economic applications of fineness variations have been discussed by Fisher (1953). He suggested that in lode deposits fineness variations could be used to indicate the type of deposit and the

conditions of formation. The behaviour of the lode at depth, the pitch of an ore shoot and the course of the mineralization channels, could be followed and predicted from fineness data. Variations in fineness throughout a mining district could indicate the magmatic source of the mineralization, and provide a more reliable zoning of the ore deposits than would be possible by other means. The amount of secondary enrichment could be determined from fineness data, as suggested by Mackay (1944), thus showing whether a drop in grade was due to the bottom of the enriched zone or the primary zone being reached. As an aid to prospecting for further ore, fineness data could add to the knowledge of the nature and distribution of the mineralization.

C. SUMMARY AND CONCLUSIONS

Gold fineness is defined as the ratio $1000 \text{ Au}/(\text{Au} + \text{Ag})$. Reported values of gold fineness vary in individual grains, rock types, deposits and regions. The change in fineness is, however, generally systematic, varying with some independent physical factor.

Alluvial gold is generally finer than the vein gold from which it is derived, and the fineness increases with the distance travelled by the gold. The increase in fineness is due, in part at least, to a surface refining action.

In lode deposits, oxidized gold is usually finer than the primary ore and its fineness decreases towards the sulphide zone. The fineness of the primary gold has been shown to both increase and decrease with increasing depth of the deposit, due to changes in the conditions of deposition on successive horizons. Primary gold fineness which increases with depth is characteristic of the type of ore deposit.

Lateral variations in gold fineness also occur both in individual deposits and on a regional scale. Variations in fineness may also be correlated with variations in grain size, in a particular deposit. In most deposits, fineness increases with increasing grade of ore, probably as a result of original hypogene conditions, such as an increase in the rate of metallization during the later stages of ore deposition, accompanied by an increase in the purity of the gold deposited.

The concentration of silver in the ore fluids and the temperature and pressure prevailing at the time of ore deposition, appear to be the main factors controlling the fineness of primary gold. There are two schools of thought as to whether early gold is purer than late gold, or not.

Fineness data can be used to indicate the type of deposit and conditions of formation; the behaviour of ore shoots, lodes and veins; the source of mineralization; the zoning of an ore deposit or mining region; and the amount of secondary enrichment.

* * * * *

SUMMARY AND CONCLUSIONS

1. Gold is very widely, but sparsely, distributed in nature.
2. It tends to be associated with definite minerals, especially pyrite, galena, arsenopyrite, chalcopyrite, pyrrhotite, sphalerite, carbonates and quartz.
3. The associated elements in gold deposits include iron, lead, copper, arsenic, bismuth, tellurium and silver. Sometimes individual deposits may be characterized by definite elements and, generally, deposits in the same mining district are characterized by the same elements.
4. Trace elements in the associated individual minerals, especially pyrite, are also characteristic for any deposit and may indicate the type of deposit.
5. The associated minerals, trace elements and elements in individual minerals are all affected by the conditions of formation. Therefore, they may indicate the type of mineralization. Generally, there is a qualitative similarity for all three in ore deposits, but quantitatively there are marked variations.
6. Sub-microscopic gold is generally confined to definite minerals. The gold may be widely dispersed in the sulphide minerals. In the native state it occurs in solid solution with the sulphides or else as minute flakes or inclusions.
7. The composition of native gold varies within individual grains, nuggets, deposits, etc. Silver, copper and iron are almost always present in gold. Common trace elements include lead, aluminium, antimony, bismuth, manganese, tin, arsenic, nickel, mercury, silicon, titanium, vanadium and magnesium. The trace element assemblage does not seem to be characteristic for an individual deposit, but may be for a metallogenetic province. The silver-gold ratio of the ore from an individual deposit appears to be affected by regional metallogenetic features. Generally, gold throughout the world has the same composition.
8. Metallurgical evidence supports the idea that silver, copper and iron occur in solid solution with gold. Lead, bismuth and tellurium are probably mechanically included in native gold, while the mode of occurrence of other elements is uncertain, though most of them can be made to alloy with gold under particular conditions.

9. Reported values for the fineness of gold vary remarkably in different types of deposits and in deposits of the same type. Fineness is defined as the ratio $1000 \text{ Au}/(\text{Au} + \text{Ag})$. Previously the base metal content had not been allowed for in calculating the gold-silver ratio.
10. Alluvial gold is generally finer than the vein gold from which it is derived, due to a surface refining action. The fineness of placer deposits increases with the distance travelled by the gold downstream.
11. Gold in the oxidized zone is usually finer than primary gold, due to a refining action. The secondary enrichment of gold is thought to be due to differential solution of silver relative to gold, the former appearing to be more easily transported than gold. To dissolve gold a manganeseiferous environment, in which nascent chlorine can be evolved, is required.
12. Fineness is found to vary vertically, either increasing or decreasing with depth of deposition.
13. There is a lateral variation in the fineness values of a single deposit or metalliferous region.
14. Fineness either increases or decreases with decreasing grain size.
15. An increase in the grade of ore is almost always accompanied by an increase in fineness. However, low-grade ores may contain patches of high quality gold. This relationship appears to be related to primary conditions of deposition.
16. The concentration of silver in the original ore fluids and the temperature-pressure conditions at the time of ore deposition, appear to be the most important factors controlling the fineness of primary gold. There is some controversy as to whether early gold is silver-rich or silver-poor.
17. Practical applications of fineness variations include the indications of the type and behaviour of an ore deposit; the magmatic source of mineralization; the regional zoning; the amount of secondary enrichment.
18. Too little work has been done on the variation in the gold-copper ratio of ores to draw any definite conclusions, though it appears that any changes will be similar to those shown by the gold-silver ratio and fineness of ores.

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