

GEOLOGICAL SURVEY CIRCULAR 612



Gold in Minerals and the Composition of Native Gold

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By Robert S. Jones and Michael Fleischer

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GOLD IN MINERALS AND THE COMPOSITION OF NATIVE GOLD

By ROBERT S. JONES and MICHAEL FLEISCHER

ABSTRACT

Gold occurs in nature mainly as the metal and as various alloys. It forms complete series of solid solutions with silver, copper, nickel, palladium, and platinum. In association with the platinum metals, gold occurs as free gold as well as in solid solution.

The native elements contain the most gold, followed by the sulfide minerals. Several gold tellurides are known, but no gold selenides have been reported, and only one sulfide, the telluride-sulfide mineral nagyagite, is known.

The nonmetallic minerals carry the least gold, and the light-colored minerals generally contain less gold than the dark minerals.

Some conclusions in the literature are conflicting in regard to the relation of fineness of native gold to its position laterally and vertically within a lode, the nature of the country rocks, and the location and size of nuggets in a streambed, as well as to the variation of fineness within an individual nugget.

INTRODUCTION

This report on the occurrence of gold in minerals and on the fineness of native gold was prepared as background material for the Heavy Metals program of the U.S. Geological Survey, an intensified program of research on new sources of heavy metals, including gold.

GENERAL GEOCHEMICAL CONSIDERATIONS

Gold belongs to group Ib of the periodic table, as do silver and copper. Its atomic number is 79, and atomic weight is 197.0; it consists of a single isotope. Its metallic radius is 1.44Å., univalent ionic radius 1.37Å., and trivalent ionic radius 0.85Å.

Gold is strongly siderophilic and somewhat chalcophilic; that is, it tends to be concentrated in the metallic phase of meteorites, with

much lower concentrations in the sulfide phase, and occurs in much lesser amounts in the silicate phase. Gold occurs in nature mainly as the metal and as various alloys, especially with silver, and as intermetallic compounds. Laboratory studies show that gold can form complete series of solid solutions with silver, copper, nickel, platinum, and palladium. Gold is commonly present in association with platinum metals; most microscopic studies have shown that free gold is present in platinum, but a recent electron-probe analysis of ferroplatinum shows uniform distribution of gold (Ottemann and Augustithis, 1967). This distribution indicates that gold and platinum are present in solid solution.

Several gold tellurides are known (table 1), but no gold selenides have been reported, and the only mineral in which gold is certainly combined with sulfur is the telluride-sulfide, nagyagite. Gold commonly occurs in sulfide minerals, but largely, if not entirely, as the free metal; it is uncertain whether any gold occurs in these minerals in true isomorphous substitution.

It is even less likely that gold is present in ionic substitution in silicate minerals. Mantei and Brownlow (1967) state, "The concentration of gold in the various minerals is probably due to an inclusion or entrapping phenomena rather than to ionic substitution. Because of its oxidation potential, it would be difficult for gold to become oxidized and thus be able to take part in ionic substitution. Krauskopf (1951) states that simple ionic gold can not exist in geological environments, although complex ions containing gold may form. Ringwood (1955) points out that Au^+ , because of its

large electronegativity, would form a very weak covalent bond, and one which would prefer not to form. Thus the gold of a crystallizing magma tends to concentrate in the residual fluids. The factors which would control the amount of gold entrapped in a given mineral would be the concentration of gold in the magma at the time of crystallization and the type of crystal structure formed by the mineral."

Helgeson and Garrels (1968), on the basis of thermodynamic calculations, think that all but marginal or low-grade hydrothermal native gold deposits form above 175°C and, at elevated temperatures, most hydrothermal solutions are probably distinctly acid. They believe that gold is present primarily in the form of aurous chloride complexes in contrast to the low-temperature considerations of Krauskopf (1951) and Cloke and Kelly (1964) who suggest that the aqueous species $AuCl_4^-$ is the principal form of dissolved gold in hydrothermal solutions.

Goni, Guillemin, and Sarcia (1967) have investigated the stability of colloidal suspensions of gold and the formation of nuggets. Stable colloidal suspensions of ionic and even metallic gold can form which can be flocculated to form nuggets. Textures common in gold deposits can be reproduced in gold films formed by the diffusion of gold solutions through silica gel.

Gold occurs in notable amounts in hydrothermal veins and in placer deposits, and to a much lesser extent in pegmatites and contact metamorphic deposits. Common minerals associated with gold in veins are quartz and pyrite. Some other common minerals associated with gold (Lincoln, 1911; Schwartz, 1944) are pyrrotite, arsenopyrite, chalcopyrite, sphalerite, galena, molybdenite, tellurides, selenides, magnetite, scheelite, feldspar, sericite, biotite, chlorite, amphiboles, garnet, tourmaline, carbonates, and fluorite.

GOLD IN MINERALS

Minerals that have been reported to contain major amounts of gold are listed on table 1. Many analyses have been made for some of the precious metals in minerals that contain little gold; those made before 1955 are listed in table 2 and those made since 1954 are in table 3. The more recent analyses have

been made by more sensitive methods, mostly by neutron activation, than the older ones, and values as low as 0.0003 ppm (part per million) are reported. However, comparatively few neutron activation analyses of rock-forming minerals have been reported in recent years. The older analyses tend to be significantly higher than more recent analyses of the same minerals. The highest gold values listed in tables 2 and 3 are reported for the native elements; next highest are for the sulfide minerals.

TABLE 1.—Major gold-bearing minerals

Gold	Au. Cubic, sp gr 19.3 (pure Au), decreasing with increasing content of Ag. Forms a complete series of solid solutions with silver (see electrum and silver, below); commonly contains 10–15 percent Ag. Also reported in percent: Cu (max 20.4), Fe (max 0.1), rarely Bi (max 2.9), Sn (max 0.3), Pb (max 0.2), Zn (max 0.8), Al (max 0.10), Mn (max 0.002). See section "Composition and Fineness of Gold."
Varieties:	
	Electrum, (Au,Ag), argentine gold with >20 percent Ag.
	Porpezite, (Au,Pd), palladian gold with 5–10 percent Pd.
	Rhodite, (Au,Rh), rhodian gold(?) with 34–43 percent Rh.
	Auricupride (cuproauride) has generally been considered to be a solid solution of gold in copper, near $AuCu_3$ in composition. Ramdohr (1967) states, however, that study of "red gold" from Laksia, Cyprus, has shown the presence of three distinct phases. Au-Cu solid solutions, the compound $AuCu_3$ with a characteristic violet color, and the compound AuCu.
	Aurosmirid, aurosmiridium (=aurian osmiridium) Au 19.3 percent. Probably a mixture containing gold. (Palache and others, 1944, p. 111).
Silver	(Ag,Au). Aurian silver, with 0–50 percent Au. Küstelite = aurian silver.
Gold-amalgam	Au_2Hg_3 (?) Au 34.2–41.6 percent.
Maldonite	Au_2Bi . Cubic. Au 64.5–65.1 percent; Bi 34.9–35.5 percent.
Aurostibite	$AuSb_2$. Cubic, pyrite type. Au 43.5–50.9 percent.
Krennerite	$AuFe_2$. Orthorhombic. Au 30.7–43.9 percent.
	Müllerine = Krennerite Speculite = Krennerite(?)

TABLE 1.—Major gold-bearing minerals—Continued

Calaverite	AuTe ₂ . Monoclinic. Au 39.2–42.8 percent.
Coolgardite	= a mixture of calaverite, coloradoite, and sylvanite.
Sylvanite	(Au,Ag)Te ₂ , with Au:Ag usually nearly 1:1, that is, AgAuTe ₄ . Monoclinic. Au 24.25–29.9 percent.
Goldschmidtite	= Sylvanite.
Kostovite	CuAuTe ₄ Au 25.2 percent (Terziev, 1966).
Petzite	Ag ₃ AuTe ₂ Au 19.0–25.2 percent.
Antamokite	= a mixture of petzite and altaite.

TABLE 1.—Major gold-bearing minerals—Concluded

Hessite	Ag ₂ Te. Monoclinic, pseudocubic. Reported to contain as much as 4.7 percent Au.
Montbrayite	Au ₂ Te ₃ . Triclinic. Au 38.6–44.3 percent.
Nagyagite	Pb ₅ Au(Te,Sb) ₄ S ₅₋₈ (?). Monoclinic (?). Au 7.4–10.2 percent.
Silberphyllinglanz	= Nagyagite.
Blatterine	= Nagyagite.
Aurobismuthinite	(Bi,Au,Ag) ₅ S ₈ (?) Au 12.3 percent; Ag 2.3 percent. Probably a mixture (Palache and others, 1944 p. 278).

TABLE 2.—Analyses of precious metals in minerals made before 1955

[Minerals containing higher amounts of gold are listed in table 1. N. D., not determined]

Mineral and locality	Gold (ppm)	Silver (ppm)	Platinum (ppm)	Remarks	Reference
Elements					
Arsenic, As					
Germany, Andreasberg, Harz ----	150	>1,000	20	One sample --	Noddack and Noddack (1931).
Copper, Cu					
Norway, Kviteseid -----	200	>1,000	.3	Two samples --	Do.
Iridosmine, (Os,Ir)					
Australia, New South Wales -----	800	-----	>1,000	Eight samples	Do.
U.S.S.R., Urals -----	>1,000	600	>1,000	-----	Do.
Iron, (Fe,Ni)					
Greenland, Ovifak, Disko -----	1-5	5-10	5	In basalt ----	Goldschmidt and Peters (1932).
United States:					
Canyon Diablo, Ariz -----	5	5	10-100	In meteorite --	Do.
Holbrook, Ariz -----	10	1	10-100	----- do -----	Do.
Mexico					
Coahuila -----	1-5	5	10-100	----- do -----	Do.
Chile, Corrizatillo -----	5-10	5-10	10	In meteorite --	Do.
Germany, Bühl, near Kassel -----	.5	5-10	.2	In basalt ----	Do.
Czechoslovakia, Knyahinya -----	10	1	10-100	In meteorite --	Do.
Portugal, Sao Juliao de Moreira --	10	5	10-100	----- do -----	Do.
Platinum, Pt					
Brazil -----	>1,000	>1,000	>1,000	One sample --	Noddack and Noddack (1931).
U.S.S.R., Urals -----	500	200	>1,000	Eleven samples.	Do.
Platiniridium, (Ir,Pt)					
Brazil -----	200	-----	>1,000	One sample --	Do.
Schreibersite, (Fe,Ni) ₃ P					
Portugal, Sao Juliao de Moreira --	1	10	1.2	In meteorite. Two samples.	Goldschmidt and Peters (1932).
Sulfides, arsenides, selenides, and tellurides					
Domeykite, Cu ₃ As					
Mexico, Paracatas -----	25	>1,000	5	One sample --	Noddack and Noddack (1931).
Argentite, Ag ₂ S					
Germany, Freiberg -----	200	>1,000	4	Two samples --	Do.

TABLE 2.—Analyses of precious metals in minerals made before 1955—Continued

Mineral and locality	Gold (ppm)	Silver (ppm)	Platinum (ppm)	Remarks	Reference
Sulfides, arsenides, selenides, and tellurides—Continued					
Berzelianite, Cu ₂ Se Sweden, Skrikerum -----	100	>1,000	10	One sample --	Noddack and Noddack (1931).
Chalcocite, Cu ₂ S United States, Butte, Mont -----	12	500	.1	Six samples -	Do.
Bornite, Cu ₅ FeS ₄ Germany, Mansfeld -----	8	>1,000	.2	Four samples--	Do.
Galena, PbS South Africa -----	30	>1,000	.8	Five samples -	Do.
Clausthalite, PbSe Germany, Tilkerode, Harz -----	250	>1,000	40	One sample --	Do.
Altaite, PbTe U.S.S.R., Altai -----	400	>1,000	10	----- do -----	Do.
Alabandite, MnS Roumania, Nagyag, Siebenbürgen--	2	30	.02	----- do -----	Do.
Sphalerite, (Zn,Fe)S Germany: Silesia -----	3	150	0	Three samples	Do.
Bühl, near Kassel -----	.5	5	---	In basalt ----	Goldschmidt and Peters (1932).
Chalcopyrite, CuFeS ₂ Germany: Clausthal -----	20	800	.1	Fifteen sam- ples.	Noddack and Noddack (1931).
Breitenbrunn, near Zwickau-----	.2	100- 1,000	---	-----	Goldschmidt and Peters (1932).
South Africa: Transvaal, Rustenburg district --	<.5	---	<.5	-----	Schneiderhöhn and Moritz (1931).
Stannite, Cu ₂ FeSnS ₄ England, Cornwall -----	2	100	.1	-----	Noddack and Noddack (1931).
Do -----	5	100	.5	-----	Goldschmidt and Peters (1932).
Czechoslovakia, Zinnwald -----	.2	100- 1,000	---	-----	Do.
Pyrrhotite, Fe _{1-x} S Norway, Frøysa -----	2	100	3	-----	Noddack and Noddack (1931).
Germany, Bühl, near Kassel -----	.5	5	---	In basalt ----	Goldschmidt and Peters (1932).
South Africa, Transvaal -----	1-10	---	10-100	From Merensky Horizon on Schildpadnest, Rustenburg district. Content of other elements: Cu, Co about 0.1 percent; Pa, 10-100 ppm; Ru, Rh, Ir, 0.1-1 ppm; Os, a trace.	Schneiderhöhn (1925).

TABLE 2.—Analyses of precious metals in minerals made before 1955—Continued

Mineral and locality	Gold (ppm)	Silver (ppm)	Platinum (ppm)	Remarks	Reference
Sulfides, arsenides, selenides, and tellurides—Continued					
Troilite, FeS					
United States, Canyon Diablo, Ariz.	0.5	10	0.5	In meteorite	Goldschmidt and Peters (1932).
Mexico:					
Coahuila -----	1-5	5	1-10	do	Do.
Ixtlahuaca -----	.2	15	6	do	Noddack and Noddack (1931).
Chile, Corrizatillo -----	.5	10	.2	do	Goldschmidt and Peters (1932).
Esthonia, Tennasilm -----	0	5	.3	do	Noddack and Noddack (1931).
Nicolite, NiAs					
Germany:					
Eiselben -----	1	10-100	---	-----	Goldschmidt and Peters (1932).
Klettenberg, Sauerland -----	10	10	.2	-----	Do.
Austria, Schladming, Styria -----	.5	100	---	-----	Do.
Pentlandite, (Ni,Fe,Co)₉S₈					
Norway, Espedalen -----	6	140	2	Two samples	Noddack and Noddack (1931).
Germany, St. Blasien, Schwarzwald	.5	10-100	.2	-----	Goldschmidt and Peters (1932).
South Africa, Rustenburg district, Transvaal -----	1.0	---	5-10	-----	Schneiderhöhn and Moritz (1931).
Siegenite, (Co,Ni)₃S₄					
Germany, Müsen near Siegen ----	1	>1,000	.5	-----	Goldschmidt and Peters (1932).
Pyrite, FeS₂					
Norway:					
Setesdalen -----	.4	10	---	Fifteen samples.	Noddack and Noddack (1931).
Sulitjelma -----	.4	70	.3	-----	Do.
Italy:					
Calceranica -----	1.1	---	---	-----	Minguzzi (1947).
Libiola, Genova Province -----	.33	---	---	Two samples	Do.
Boccheggiano, Grosseto -----	.12	---	---	-----	Do.
Chuch e Servette -----	.95	---	---	-----	Do.
Pestarena -----	200	---	---	-----	Do.
Lavanchetto -----	20	---	---	-----	Do.
Alfenza -----	6.5	---	---	Crystalline aggregate contained 12 ppm Au and a crystal contained 0.93 ppm Au. Two samples.	Do.
South Africa:					
Rustenburg district, Transvaal ---	5-10	---	10-50	Nickeliferous	Schneiderhöhn and Moritz (1931).
Witwatersrand -----	3	---	---	Three samples	Hegermann and Leybold (1954).
Sperrylite, PtAs₂					
Canada, Vermillion mine, Ontario--	40	300	>1,000	One sample	Noddack and Noddack (1931).

TABLE 2.—Analyses of precious metals in minerals made before 1955—Continued

Mineral and locality	Gold (ppm)	Silver (ppm)	Platinum (ppm)	Remarks	Reference
Sulfides, arsenides, selenides, and tellurides—Continued					
Cobaltite, CoAsS					
Canada, Cobalt, Ontario -----	5	5	0.1	-----	Goldschmidt and Peters (1932).
Norway, Skutterud -----	10	200	2	One sample --	Noddack and Noddack (1931).
	.5	1	----	-----	Goldschmidt and Peters (1932).
Sweden, Tunaberg -----	.5	10	.5	-----	Do.
Germany:					
Dreikönigsstollen Buchholz, Saxony	.3	10	.1	-----	Do.
Glücksbrunn, Altenstein, Sachsen-Meine -----	3	5	.1	-----	Do.
Gersdorffite, NiAsS					
Germany:					
Müsen, near Siegen -----	10-100	10-100	.1	-----	Do.
Friedensgrube, Lichtenberg, Oberfranken -----	10-100	10-100	.1	-----	Do.
Lobenstein, Vogtland, Thüringen	5	1	----	-----	Do.
Michaelis Fundgrube, Triebel, near Zwickau -----	10-100	10-100	.1	-----	Do.
Ullmannite, NiSbS					
Germany:					
Müsen, near Siegen -----	20	20	.5	-----	Do.
Salchendorf, near Siegen -----	10	100- 1,000	----	-----	Do.
Landeskrone, Willnsdorf, near Siegen -----	.5	10-100	.2	-----	Do.
Safflorite, CoAs ₂					
Germany:					
Schneeberg, Saxony -----	.3	10-100	----	-----	Do.
Dachsberg, near Riechelsdorf ---	5	.5	.1	-----	Do.
Rammelsbergite, NiAs ₂					
Germany, Gessellschafter Zug, Schneeberg, Saxony -----	.3	5	----	-----	Do.
Marcasite, FeS ₂					
Germany, Westphalia -----	4	100	.1	One sample --	Noddack and Noddack (1931).
Arsenopyrite, FeAsS					
Norway, Skutterud -----	8	90	.4	Four samples	Do.
Germany, Ehrenfriedersdorf, Saxony -----	.5	10	----	-----	Goldschmidt and Peters (1932).
Molybdenite, MoS ₂					
United States, Climax, Colo -----	.05	100	.05	-----	Do.
Australia, Kingsgate, Glenn Innes, New South Wales -----	1-10	100	.02	-----	Do.
Czechoslovakia, Zinnwald -----	.1	.2	.05	-----	Do.
Germany:					
Sadisdorf near Schmiedeberg, Saxony -----	5	10-100	1	-----	Do.
Altenberg, Saxony -----	.2	2	.2	-----	Do.
Norway:					
Telemarken -----	.5	4	.04	Three samples	Do.
Sörumsassen near Drammen ---	.5	10-100	.05	-----	Do.
Råde, Østfold -----	.05	10	----	-----	Do.
Undalen -----	.05	>100	----	With chalcop- pyrite.	Do.

TABLE 2.—Analyses of precious metals in minerals made before 1955—Continued

Mineral and locality	Gold (ppm)	Silver (ppm)	Platinum (ppm)	Remarks	Reference
Sulfides, arsenides, selenides, and tellurides—Continued					
Skutterudite, CoAs ₃					
Germany:					
Niederrasmstadt near Darmstadt	0.3	1,000	---	-----	Goldschmidt and Peters (1932).
Riechelsdorf, Hessen	2.7	10	---	Two samples	Do.
Bieber, Hessen	.1	1-5	---	-----	Do.
Frauenbreitung, Saxony-					
Meiningen	.3	10-100	---	-----	Do.
Schneeberg, Saxony	.5	100-	---	-----	Do.
		1,000			
Hasserode, Harz	5	10	---	-----	Do.
Austria, Schladming, Styria	.3-5	5	---	-----	Do.
Sulfosalts					
Tetrahedrite, Cu ₁₂ Sb ₄ S ₁₃					
England, Cornwall	8	>1,000	2	-----	Noddack and Noddack (1931).
Austria, Tyrol	60	>1,000	.2	Seven samples	Do.
Germanite, Cu ₃ (Ge,Fe)S ₄					
South-West Africa, Tsumeb	40	800	.2	One sample	Do.
Enargite, Cu ₃ AsS ₄					
United States, Butte, Mont	15	>1,000	.3	do	Do.
Argyrodite, Ag ₈ GeS ₆					
Bolivia	90	>1,000	0	do	Do.
Halides					
Halite, NaCl					
England, Cheshire	0.103	N.D.	N.D.	Two samples	Liversidge (1897).
Germany, Stassfurt	.132	N.D.	N.D.	One sample	Do.
Sylvite, KCl					
Germany, Mecklenburg	.003	N.D.	N.D.	do	Friedrick (1906).
Carnallite, KMgCl ₃ ·6H ₂ O					
Germany, Bernburg	.012	N.D.	N.D.	do	Do.
Simple oxides					
Pyrolusite, MnO ₂					
Czechoslovakia, Platten, Bohemia	0.2	4	10	Four samples	Noddack and Noddack (1931).
Cassiterite, SnO ₂					
Bolivia, Potosi	.5	10-100	---	-----	Goldschmidt and Peters (1932).
Indonesia, Bangka Island	.5	10	---	-----	Do.
Germany, Breitenbrunn near					
Zwickau, Saxony	.5	10	---	Three samples	Do.
Czechoslovakia, Schönfeld near					
Schlaggenwald	.5	5	---	-----	Do.
South-West Africa:					
Sandamab	.5	10	.2	-----	Do.
Nubeb	.5	1	.2	-----	Do.

TABLE 2.—Analyses of precious metals in minerals made before 1955—Continued

Mineral and locality	Gold (ppm)	Silver (ppm)	Platinum (ppm)	Remarks	Reference
Oxides containing uranium, thorium, or zirconium					
Uraninite, UO ₂					
Norway, Brevik -----	0.1	2	0.2	One sample --	Noddack and Noddack (1931).
Czechoslovakia, Jachymov -----	.03	5	.2	Two samples --	Do.
Thorianite, ThO ₂					
Ceylon -----	.05	2	.1	One sample --	Do.
Oxides containing OH					
Psilomelane, (Ba,H ₂ O) ₂ Mn ₂ O ₁₀					
Germany, Harz -----	2	50	2	Two samples --	Noddack and Noddack (1931).
Multiple oxides					
Chromite, (Mg,Fe) ₂ CrO ₄					
United States:					
Mineral Hills, Pa -----	0.2	1	1	-----	Goldschmidt and Peters (1932).
Lancaster County, Texas, Pa -----	.2	1	-----	-----	Do.
Norway, Feragen, Bebiet -----	.2	1	-----	-----	Do.
Hausmannite, Mn ₂ O ₄					
Sweden, Långban -----	.1	10	-----	Two samples --	Noddack and Noddack (1931).
Multiple oxides containing Nb, Ta, and Ti					
Columbite, (Fe,Mn)(Nb,Ta) ₂ O ₆					
Norway, Arendal -----	0.05	2	3	Twenty-three samples.	Noddack and Noddack (1931).
Silicates					
Plagioclase, (Na,Ca)(Al,Si) ₂ Si ₂ O ₆					
South Africa, Rustenburg district, Transvaal -----	<0.5	-----	<0.5	-----	Schneiderhöhn and Moritz (1931).
Pyroxenes:					
Bronzite, (Mg,Fe)SiO ₃					
South Africa, Rustenburg district, Transvaal -----	<.5	-----	1-5	-----	Do.
Diallage, Ca(Mg,Fe)Si ₂ O ₆					
South Africa, Rustenburg district, Transvaal -----	.5	-----	1-5	-----	Do.
Olivine, (Mg,Fe) ₂ SiO ₄					
South Africa, Rustenburg district, Transvaal -----	.5	-----	1.0	-----	Do.
Gadolinite, Y ₂ FeBe ₂ Si ₂ O ₆					
Norway, Iveland -----	.2	4	2	-----	Noddack and Noddack (1931)
Arandisite, (tin silicate?)					
South-West Africa, Arandis -----	.5	5	.2	-----	Goldschmidt and Peters (1932).
Hellandite, silicate of Ca and Y					
Norway, Kragerø -----	.1	1	.1	One sample --	Noddack and Noddack (1931).

TABLE 2.—Analyses of precious metals in minerals made before 1955—Continued

Mineral and locality	Gold (ppm)	Silver (ppm)	Platinum (ppm)	Remarks	Reference
Phosphates					
Triplite, (Mn,Fe) ₂ (PO ₄)F South-West Africa, Sandamab ----	0.5	5	0.2	-----	Goldschmidt and Peters (1932).
Nitrates					
Soda Niter, NaNO ₃ Chile -----	0.110	N.D.	N.D.	One sample --	Liversidge (1897).
Sulfates					
Anhydrite, CaSO ₄ Germany, Plömnitz -----	0.007	N.D.	N.D.	One sample --	Friedrick 1906).
Gypsum, CaSO ₄ ·2H ₂ O United States: Salina, N.Y -----	.083	N.D.	N.D.	Silurian. One sample.	Lincoln (1911).
Grand Rapids, Mich -----	.083	N.D.	N.D.	Mississippian. One sample.	Do.
Kainite, KMg(SO ₄)Cl·3H ₂ O Germany, Plömnitz -----	.003	N.D.	N.D.	One sample --	Friedrick (1906).

Both Anoshin and Potap'yev (1966) and Shcherbakov and Perezhugin (1964) show that the gold in the quartz exceeds that in the feldspars by a factor of 2.7. Shcherbakov and Perezhugin noted from the analyses of monomineralic fractions of igneous rocks that the average gold content decreases from magnetite and ferromagnesian silicates to feldspars. They reported (table 3) the gold content of the major rock-forming minerals as follows: quartz, 11 ppb (parts per billion); feldspar, 4 ppb; biotite, 4 ppb; muscovite, 3.8 ppb; amphibole, 5.9 ppb; pyroxene, 16 ppb; olivine, 14 ppb; and magnetite, 48 ppb.

Mantei and Brownlow (1967) have made many neutron activation analyses of minerals from the Marysville quartz diorite stock (table 3). The diorite has an appreciably higher gold content than the average diorite, and most of its component minerals have unusually high gold contents. The reported gold contents increase from quartz and feldspar (65 ppb) to biotite (76 ppb) and reach a maximum in hornblende (100 ppb). The gold content of magnetite was found to be only 37 ppb, in contrast to the findings of Shcherbakov and Perezhugin (1964) who report more gold

in magnetite than in the silicate minerals. Mantei and Brownlow accounted for the lower gold content of magnetite, compared with other minerals they analyzed, by pointing out that the structure of magnetite is relatively closed compared to the structures of biotite and hornblende and that "magnetite may have formed before the silicates, at a time when the concentration of gold in the magma was fairly low."

Badalov (1965) examined the average amounts of gold, silver, selenium, and tellurium in the disseminated copper-molybdenum deposits of the Almalyk district in the U.S.S.R. The sequence of the formation of the predominate minerals in the ores was from earliest to latest: magnetite, molybdenite, pyrite, chalcopyrite, sphalerite, and galena. Pyrite is by far the most abundant mineral and carries 3 ppm gold. Chalcopyrite is the second most abundant mineral and was the chief "concentrator" of gold; it contains 22 ppm. Native gold is common, and gold tellurides are rare.

Noddack and Noddack (1931) looked for but did not detect gold in the following minerals: allanite, alvite (variety of zircon), andalusite, aragonite, beryl, brewsterite, bronzite,

TABLE 3.—*Analyses of gold in minerals made since 1954*

[Minerals containing higher amounts of gold are listed in table 1]

Mineral and locality	Gold (ppm)	Remarks	Reference
Elements			
Arsenolamprite, As Germany, Thüringia -----	5	Silver, 1 ppm. Spectrographic analysis.	Fischer (1958-59).
Iron, (Fe, Ni) U.S.S.R., Sikhote-Alin' -----	1.15	One sample of meteorite. In troilite. 0.067 ppm Au. Neutron activation analysis.	Shcherbakov and Perezhugin (1964).
Sulfides			
Arsenopyrite, FeAsS U.S.S.R., Central Chukotki -----	200	Samples from veins and ore minerals.	Sidorov (1966).
Germany, Thüringia -----	.5	Silver, 15 ppm. Spectrographic analysis.	Fischer (1958-59).
Chalcopyrite, CuFeS ₂ U.S.S.R., Almalyk -----	.22	Chalcopyrite is the chief "concentrator" but pyrite is the chief "carrier." Content in parts per million of Pd, 0.21, Pt, 0.02, Ag, 0.02. Analyses by fire assay followed by spectrographic.	Badalov (1965) and Badalov and Terekhovich (196 ^a).
Germany, Thüringia -----	.02	Pd, 0.2 ppm, Ag 10 ⁻³ percent. Spectrographic analysis.	Fischer (1958-59).
Cobaltite, CoAsS Germany, Thüringia -----	5	Silver, 20 ppm. Spectrographic analysis.	Do.
Galena, PbS U.S.S.R.: Central Chukotki -----	5	Silver, 450 ppm. Pd, 0.032 ppm. Analyses by fire assay followed by spectrographic.	Sidorov (1966). Badalov and Terekhovich (196 ^a).
Almalyk -----	13		
Germany, Thüringia -----	.01	Silver, 20-100 ppm. Spectrographic analysis.	Fischer (1958-59).
Molybdenite, MoS ₂ Germany, Thüringia -----	.02	Content in parts per million of: Ru, 0.03, Rh, 0.4, Pd, 0.6, Pt, 0.4, Ag, >10 ⁻² percent.	Do.
Pyrite, FeS ₂ East Greenland -----	.016	Content in parts per million of: Ag, 60, Se, 40, and Te, 16. Pyrite is the chief "carrier" but chalcopyrite is the chief "concentrator" of gold.	Vincent and Crocket (1960). Badalov (1965).
U.S.S.R.: Almalyk -----	3		
Do -----	3.5	Silver, 36 ppm, Pt, 0.014 ppm. Analyses by fire assay followed by spectrographic.	Badalov and Terekhovich (196 ^f).
Central Chukotki -----	10	Samples from veins and ore minerals.	Sidorov (1966).
Germany, Thüringia -----	.2	Silver, 5 ppm. Spectrographic analysis.	Fischer (1958-59).

TABLE 3.—Analyses of gold in minerals made since 1954—Continued

Mineral and locality	Gold (ppm)	Remarks	Reference
Sulfides—Continued			
Pyrrhotite, Fe _{1-x} S			
East Greenland -----	0.003	Analyses by neutron activation	Vincent and Crocket (1960).
U.S.S.R., Central Chukotki -----	2	Samples from veins and ore minerals.	Sidorov (1966).
Sphalerite, (Zn, Fe)S			
U.S.S.R., Central Chukotki -----	500	----- do -----	Do.
Stibnite, Sb ₂ S ₃			
U.S.S.R., Central Chukotki -----	20	----- do -----	Do.
Germany, Thüringia -----	.9	Silver, 2 ppm. Spectrographic analysis.	Fischer (1958-59).
Troilite, FeS			
United States:			
Canyon Diablo, Ariz -----	.10	One sample of meteorite. Analysis by neutron activation.	Baedecker (1967).
Sardis, Ga -----	.23	One sample of meteorite found in rocks of Miocene age. Analysis by neutron activation.	Do.
U.S.S.R., Sikhote-Alin' -----	.67	One sample of meteorite. The iron part of this meteorite contained 1.15 ppm Au.	Shcherbakov and Perzhogin (1964).
Ullmanite, NiSbS			
Germany, Thüringia -----	1	Silver, 10 ppm. Spectrographic analysis.	Fischer (1958-59).
Sulfosalts			
Tetrahedrite, Cu ₁₂ Sb ₄ S ₁₃			
Germany, Thüringia -----	0.02	Silver, 20-100 ppm. Spectrographic analysis.	Do.
Oxides			
Magnetite, Fe ₃ O ₄			
United States, Helena, Mont -----	0.037	Forty-four samples from the Marysville quartz diorite stock, 20 miles northwest of Helena, Mont. Fifty-one analyses made of these samples which ranged in gold from 0.003 to 0.329 ppm. Analyses by neutron activation.	Mantei and Brownlow (1967).
U.S.S.R., Altai-Sayan folded belt (?) -----	.048	Seven samples. Analyses by neutron activation.	Shcherbakov and Perzhogin (1964).
Pyrolusite, MnO ₂			
Germany, Thüringia -----	<.01	Silver, 3 ppm. Spectrographic analysis.	Fischer (1958-59).
Quartz, SiO ₂			
U.S.S.R.:			
Central Chukotki -----	2	Samples from veins and ore minerals.	Sidorov (1966).
Altai and Transbaikal -----	.0008	Analyses by neutron activation.	Anoskin and Potap'yev (1966).
Altai-Sayan folded belt (?) -----	.011	Analysis by neutron activation. Nine samples.	Shcherbakov and Perzhogin (1964).

TABLE 3.—Analyses of gold in minerals made since 1954—Continued

Mineral and locality	Gold (ppm)	Remarks	Reference
Oxides—Continued			
Quartz and feldspar United States, Helena, Mont.-----	0.065	Ten samples from the Marysville quartz diorite stock, 20 miles northwest of Helena, Mont. Twelve analyses made of these samples which ranged in gold from 0.006 to 0.176 ppm. Analyses by neutron activation.	Mantei and Brownlow (1967).
Wad, Mn oxide Germany, Thüringia -----	<.01	Silver, 5 ppm. Spectrographic analysis.	Fischer (1958-59).
Silicates			
Feldspars, Al silicates with K, Na, and Ca U.S.S.R., Altai-Sayan folded belt (?) -----	0.0040	Twenty-seven samples. Analyses by neutron activation.	Shcherbakov and Perezhugin (1964).
Altai and Transbaikal -----	.0003	Analysis by neutron activation.	Anoshin and Potan'yev (1966).
Microcline, $KAlSi_3O_8$ U.S.S.R., S. E. Altai -----	.018	One sample from a migmatite. Analysis by neutron activation.	Shcherbakov and Perezhugin (1964).
Amphiboles, hydrous silicates with chiefly Ca, Mg, Fe, Al, and Na U.S.S.R.:			
Altai-Sayan folded belt (?) ----	.0059	Fourteen samples analyzed by neutron activation method.	Do.
Kuznetsk, Ala-Tau -----	.077	Two samples analyzed by neutron activation.	Do.
Hornblende, $Ca_2Na(MgFe^{+2})_4Al, Fe^{+3}Ti)_3Si_8O_{22}(O,OH)_2$ United States, Helena, Mont. ----	.100	Thirty-seven samples from the Marysville quartz diorite stock, 20 miles northwest of Helena, Mont. Forty-two analyses made of these samples which ranged in gold from 0.003 to 0.823 ppm. Analyses by neutron activation.	Mantei and Brownlow (1967).
Pyroxene, silicates of Ca, Mg, Fe, and others U.S.S.R., Altai-Sayan folded belt (?) -----	.016	Eight samples analyzed by neutron activation.	Shcherbakov and Perezhugin (1964).
Tourmaline, complex silicate of B and Al U.S.S.R., Altai-Sayan folded belt (?) -----	.012	Four samples analyzed by neutron activation.	Do.
Muscovite, $KAl_2(AlSi_3)O_{10}(OH)_2$ U.S.S.R., Altai-Sayan folded belt (?) -----	.0038	Seven samples analyzed by neutron activation.	Do.

TABLE 3.—Analyses of gold in minerals made since 1954—Continued

Mineral and locality	Gold (ppm)	Remarks	Reference
Silicates—Continued			
Biotite, $K(Mg, Fe)_3(AlSi_3)O_{10}(OH)_2$ United States, Helena, Mont -----	0.076	Forty-four samples from the Marysville quartz diorite stock, 20 miles northwest of Helena, Mont. Fifty-three analyses made of these samples which ranged in gold from 0.002 to 0.924 ppm. Analyses by neutron activation.	Mantei and Brownlow (1967).
U.S.S.R., Altai-Sayan folded belt (?) -----	.0040	Eight samples analyzed by neutron activation.	Shcherbakov and Perezhogin (1964).
Altai -----	.0091	Three samples from granite which were analyzed by neutron activation.	Do.
Olivine, $(Mg, Fe)_2SiO_4$ U.S.S.R., Altai-Sayan folded belt (?) -----	.014	Two samples analyzed by neutron activation.	Do.
Sphene, $CaTiSiO_5$ U.S.S.R., Altai-Sayan folded belt (?) -----	.0039	Two samples analyzed by neutron activation.	Shcherbakov and Perezhogin (1964).

cristobalite, daubreelite (from meteorites), diopside, epidote, euclase, garnet, gersdorffite, harmotome, hauerite, heulandite, hornblende, kaolin, lepidolite, leucite, malachite, malacon, molybändocker [ilsemannite], molybdosodalite, muscovite, nepheline, olivine, orpiment, orthoclase, pyroxene, rhodochrosite, rutile, serpentine, stibnite, tantalite, thalenite, and thortveitite. The lower limit of detection of the analytical method they used seems to be about 10 ppb. Other specimens of some of these minerals analyzed by neutron activation methods also show less than 10 ppb Au (table 3).

Platinum exceeds gold in meteorites, as well as in metasilicate minerals and orthosilicate minerals.

COMPOSITION AND THE FINENESS OF GOLD

Samples of native gold from 48 places throughout the world have been analyzed for selected elements (Gay, 1963). The frequency of occurrence of 30 elements detected (in order of frequency) is as follows:

Detected in 90–100 percent of the samples ----- Ag, Cu, Fe
 Detected in 18.8–37.6 percent of the samples ----- Pb, Ti, Al, Sb, Hg, V, Bi, Mn, Si, As, Sn
 Detected in 6.3–14.6 percent of the samples ----- Mg, Ni, Ca, Zn, Pd, Pt, Te
 Detected in 2.1–4.2 percent of the samples ----- B, Co, Cr, Mo, Cd, Rh, Sr, W, Zr

It is probable that not all the elements in the foregoing list were looked for by most analysts.

Warren and Thompson (1944) studied the composition of 66 samples of native gold, about 75 percent of which originated in Canada. All samples contained silver, copper, and iron. The number of occurrences of the various other elements in the gold were: titanium, 52; mercury, 42; manganese, 40; lead, 37; vanadium, 28; tin, 22; antimony, 21; bismuth, 19; arsenic, 17; zinc, 15; cadmium, 14; tellurium, 8; platinum, 3; and palladium, 2. Silver was usually present in amounts exceeding 0.5 percent and

copper was usually present in amounts from 0.1 percent to 0.5 percent. The remaining elements, when present in the gold, were usually in amounts of less than 1 percent.

Wise (1964), in a study of binary alloys of gold, gives the various maximum high-temperature solid solubilities of elements in gold as follows:

100 percent	-----	Ag, Cu, Ni, Pd, Pt
46 percent	-----	Fe
21.5~19 percent	-----	Cd, Cr, Hg
13 percent	-----	Zn
10.9-7.7 percent	-----	Mn, Ta, Co, In
5.2-1.2 percent	-----	V, Ga, Sn, Mg, Al, Ti, Ge
<1 percent	-----	As, Bi, Ca, Mo, Pb, Pr, Rh, Sb, Th, Tl, U, and per- haps others.

The fineness of gold, and especially its relation to the genesis of gold deposits, has been studied by numerous workers (Gay, 1963; Sundell, 1936; Mertie, 1940). Fineness refers to the ratio of gold to the sum of the gold plus the silver in the naturally occurring alloys and is defined as 1,000 times $Au/(Au+Ag)$.

Mertie (1940) noted that pure gold has not been found in nature, but that gold is always alloyed with silver and a small amount of the base metals such as iron and copper. The purest gold reported by Mertie was from the Great Boulder mine, in the Kalgoorlie district of Western Australia; it was 999.1 fine. Mertie concluded that fineness is rarely less than 600 and is generally never less than 400, although Lincoln (1911) reported a fineness of 246 for silver-gold alloys in some mafic igneous rocks.

The color of gold in polished section is an index of its fineness, according to Eales (1961). Nearly pure gold has a golden color with a ruby tint. With increasing amounts of silver, the color changes to yellow and eventually becomes a pale silvery yellow color as in electrum. Others have noted color differences in gold due to variations in fineness (Mather, 1937; Russell, 1929; Edwards, 1958).

Boyle (1960), Ward (1958), and Lincoln (1911) have commented on the fineness of gold in different country rocks. Boyle thought that the fineness of gold in lode deposits reflected the nature of the country rock and

that this seemed to indicate that the deposits were formed by diffusion of gold and silver through the country rock. For instance, in the Yellowknife district of Canada, gold in deposits in greenstone has a gold-silver ratio of 5:1 (= fineness 833), whereas gold in quartz lenses in sedimentary rocks has a ratio of 3.5:1 (= fineness 778). Ward observed that gold in some ore bodies in Western Australia that are genetically related to albite porphyry intrusives has a gold to silver ratio greater than 9:1 (= fineness 900). Lincoln noted that the fineness of gold is higher in silicic igneous rocks than in mafic varieties; gold in silicic igneous rocks averages 979 in fineness, that in intermediate types 451, and that in mafic types 245.

Native gold at the surface and in the oxidized zone of a mineral deposit is usually finer than is the native gold in the unoxidized ore (Don, 1898; Fisher, 1945; Colin, 1946; MacGregor, 1928; Mackay, 1944; Mills, 1954, and Gay, 1963). Below the oxidized zone, however, gold fineness seems to be largely independent of depth (Gay, 1963). A small decrease in the fineness of gold with depth in the Lily mine, Republic of South Africa, is reported by Anhaeusser (1966) and shown in table 4. On the other hand, average gold fineness in the Zwartkopje shoot in the Sheba mine, Republic of South Africa, increases with depth from the 14 level (about 910 fine) to the 26 level (about 950 fine) within a vertical distance of about 550 feet (Gay, 1964).

TABLE 4.—Variations in fineness of gold with depth, Lily Mine, Transvaal, South Africa

[After Anhaeusser, 1966]

Level	Depth in feet below 2,600-foot datum plane	Gold (percent)	Silver (percent)	Fineness
70-foot	200	91.50	8.50	915
1	260	91.15	8.85	911.5
1½	340	90.78	9.22	903
2	420	89.04	10.96	890

Gold fineness was noted by Gay (1963) to vary from east to west in some Witwatersrand deposits as follows: 865.8, 884.0, 870.6, 926.0, 912.0, 924.0, and 970.0. Sharwood (1911) reports some lateral variation in fineness of bullion from mines in the Lead district, South Dakota; as shown in table 5, the range in fineness is small.

TABLE 5.—*Fineness, in percent, of mill bullion prior to 1882 at the Homestake mine, South Dakota*
[Sharwood, 1911]

Mine	Gold	Silver	Base metal	Fineness
Homestake	82.0	17.0	1.0	828
Highland	83.0	15.5	1.5	843
Terra	82.5	16.0	1.5	838
Deadwood	85.0	14.0	1.0	859
De Smet	82.0	17.0	1.0	828

Lateral variation in fineness is shown by analyses of the bullion from nine representative mines in Gilpin County, Colo. (Collins, 1902). During the period 1870 to 1880, the fineness ranged from mine to mine from 753 to 897, and during the period 1880 to 1890, from 716 to 894. The average fineness of all the bullion from these mines changed little during the two periods; it was 799 for the first and 789 for the second.

Eales (1961) studied the silver content of gold from four hydrothermal deposits in Southern Rhodesia. Gold that mineragraphic studies show to have crystallized early, and that is enclosed in chalcopyrite and sphalerite, contains more silver than does gold that crystallized later.

The fineness of gold varies directly with particle size in some deposits and inversely with particle size in others (Gay, 1963).

For ore deposits in general, the fineness of the contained gold increases as the grade of ore increases; (Eales, 1961; Lawn, 1924; MacGregor, 1928; and Mackay, 1944).

Fisher (1950) concluded that fineness used with other criteria furnishes a sensitive and reliable guide to the relative temperature of ore formation, at least within the epithermal and the upper part of the mesothermal range of temperatures. The fineness of epithermal gold is from 500 to 700. Near the bottom of the epithermal zone (corresponding to the leptothermal zone of Graton, 1933), the fineness is about 700 and may be as much as 800. The fineness of mesothermal gold varies from 750 to 900, with 850–870 being common. The fineness of hypothermal gold is always greater than 800. Fineness of 900 or more results from oxidation under conditions favoring the removal of silver.

Gay (1963) observed that commonly the fineness of placer gold increases downstream from its source. This increase is explained by leaching of the silver and redeposition of

the gold. Shcherbina (1956) explains that the high ratio of silver to gold, 37.5% (Mason, 1952) in sea waters, compared to only about 10 (Vinogradov, 1956) for the lithosphere as a whole, is an indication of the greater mobility of silver.

Mertie (1940) says that in some Alaskan paystreaks the fineness of gold increases downstream from its source, but in others the fineness changes either erratically or not at all. He cites an Alaskan placer gold deposit that was derived from lodes in Tertiary quartz monzonite. The source lodes were being actively mined around 1940, and information on the fineness of both lode and placer gold indicates that the fineness does not increase progressively downstream.

Fineness varies not only from grain to grain but also within grains (Gay, 1963). Some grains are finer in the center than on the surface (Head, 1935), although Eales (1961) has noted the reverse. Gold extracted by McConnell (1907) from the outer surface of a nugget assayed 60–70 parts per thousand finer than gold from the inside of the nugget, and his findings have been cited as evidence that surface waters dissolve an appreciable amount of silver from alluvial gold. However, the difference could have been due to the original character of the primary lode gold or to surficial enrichment of the gold in the zone of oxidation before it was freed (Mertie, 1940). Very fine grained placer gold is usually finer than the coarse gold (Hite, 1930; Sundell, 1936; Fisher, 1945; and Colin, 1946). However, Mertie (1940) reports that in any one paystreak, and at any one place in the paystreak, the reverse is usually true.

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