Gold Deposits in Metamorphic Rocks—Part I

U.S. GEOLOGICAL SURVEY BULLETIN 1857–D

U.S. DEPARTMENT OF THE INTERIOR

March 3, 1849

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

Alaska Distribution Section, U.S. Geological Survey,
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following Geological Survey Public Inquiries Offices, all of which are authorized agents of the Superintendent of Documents:

- **WASHINGTON, D.C.**--Main Interior Bldg., 2600 corridor, 18th and C Sts., NW.
- **DENVER, Colorado**--Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**--Federal Bldg., Rm. 7638, 300 N. Los Angeles St.
- **MENLO PARK, California**--Bldg. 3 (Stop 533), Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**--503 National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**--Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**--Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**--U.S. Courthouse, Rm. 678, West 920 Riverside Ave..
- **ANCHORAGE, Alaska**--Rm. 101, 4230 University Dr.
- **ANCHORAGE, Alaska**--Federal Bldg, Rm. E-146, 701 C St.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following Geological Survey offices:

- **ROLLA, Missouri**--1400 Independence Rd.
- **DENVER, Colorado**--Map Distribution, Bldg. 810, Federal Center
- **FAIRBANKS, Alaska**--New Federal Bldg., 101 Twelfth Ave.

Chapter D

Gold Deposits in Metamorphic Rocks—Part I

Gold in the United Verde Massive Sulfide Deposit, Jerome, Arizona

By ED DEWITT and JEROME WAEGLI

The Alaska-Juneau and Treadwell Lode Gold Systems, Southeastern Alaska

By THOMAS D. LIGHT, DAVID A. BREW,
and ROGER P. ASHLEY

U.S. GEOLOGICAL SURVEY BULLETIN 1857

GEOLOGY AND RESOURCES OF GOLD IN THE UNITED STATES

DANIEL R. SHAWE and ROGER P. ASHLEY, Scientific Editors
L.M.H. CARTER, Technical Editor

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

March 3, 1849

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1989

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center
Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Gold deposits in metamorphic rocks.

(Geology and resources of gold in the United States) (U.S. Geological Survey bulletin ; 1857)
Bibliography: p.
Supt. of Docs. no.: I 19.3:1857–D
Contents: pt. 1. Gold in the United Verde massive sulfide deposit, Jerome, Arizona / by Ed DeWitt and Jerome Waegli. The Alaska–Juneau and Treadwell Lode gold systems, southeastern Alaska / by Thomas D. Light, David A. Brew, and Roger P. Ashley.
1. Gold ores—Arizona—Jerome Region. 2. Gold ores—Alaska—Juneau Region. 3. Rocks, Metamorphic—Arizona—Jerome Region. 4. Rocks, Metamorphic—Alaska—Juneau Region. 5. Geology—Arizona—Jerome Region. 6. Geology—Alaska—Juneau Region. I. DeWitt, Ed. II. Geology Survey (U.S.) III. Series. IV. Series: U.S. Geological Survey bulletin ; 1857.
QE75.B9 no. 1857 557.3 s [553.4'1'0973] 89–600195
[TN423.A75]

CONTENTS

Gold in the United Verde massive sulfide deposit, Jerome, Arizona

The Alaska-Juneau and Treadwell lode gold systems, southeastern Alaska

FIGURES

TABLES

GEOLOGY AND RESOURCES OF GOLD IN THE UNITED STATES

Gold Deposits in Metamorphic Rocks—Part I

Gold in the United Verde Massive Sulfide Deposit, Jerome, Arizona

By Ed DeWitt *and* Jerome Waegli[1]

Abstract

The Early Proterozoic volcanogenic massive sulfide deposit at the United Verde mine, Jerome, Arizona, is one of the largest massive sulfide deposits in North America and has produced more than 1.3 million troy ounces of gold. The unmined, zinc-rich part of the deposit is estimated to contain about 400,000 troy ounces of gold; the entire unmined part of the deposit may contain more than 1.0 million ounces of gold. The deposit is localized at the top of a quartz porphyry, a rhyolitic flow complex in the Cleopatra Member near the top of the Deception Rhyolite, a sequence of 1.76–1.78 billion-year-old rhyolitic flows, tuffs, and intrusive rocks. Alteration and mineralization styles in the deposit are typical of Archean and Proterozoic volcanogenic massive sulfide deposits in North America. From stratigraphic bottom to top, the ore body consists of a sericitic and chloritic alteration pipe in the Cleopatra, a zone of massive chlorite and stringer-zone ore rich in copper, pyritic massive sulfide ore that is zoned from a copper-rich bottom to a zinc-rich top, and chert-rich ore that caps the deposit.

Alteration studies indicate that volume loss during chloritization and mass transfer of constituents during hydrothermal alteration in the chloritic alteration pipe have drastically changed concentrations of CaO, Na_2O, K_2O, Al_2O_3, SiO_2, volatile constituents, total iron, rubidium, strontium, cesium, uranium, thorium, manganese, scandium, zirconium, niobium, yttrium, tantalum, hafnium, and rare-earth elements (especially light rare earths). Sulfur isotope ratios of pyrite, sphalerite, and galena cluster between -2.8 and $+0.2$ per mil and indicate either an overwhelming contribution of igneous-related sulfur or derivation of sulfur from restricted or stagnant bottom water that was not in contact with a sulfate-rich ocean reservoir. Lead isotope data are most easily explained by postulating a mixing of lead from sedimentary and igneous sources during evolution of the hydrothermal system.

Gold within the United Verde deposit is concentrated in the pyritic massive sulfide ore and chert-rich ore; stringer-zone (chlorite schist) ore contains very low grades of gold. Concentrations of gold for various ore types are: pyritic massive sulfide and zinc-rich massive sulfide ore, 0.02 to 0.06 oz Au/ton; chert-rich ore, as high as 0.15 oz Au/ton; chlorite schist, 0.002 to 0.006 oz Au/ton. Statistical analysis of different ore types indicates the best correlation of gold to be with combined copper and zinc. A major observation is that zinc-rich massive sulfide ore contains grades of gold as high as or higher than those of zinc-poor ore.

INTRODUCTION

The United Verde mine and the surrounding Verde mineralized district (Keith and others, 1983; Keith and others, 1984) are on the eastern slope of the Black Hills, near Jerome, Yavapai County, Ariz., 64 km southwest of Flagstaff (fig. D1) and about 140 km north of Phoenix. Small massive sulfide deposits extend 9 km south-southeast from Jerome, but more than 98 percent of the production from the Verde district has come from the United Verde and United Verde Extension mines at Jerome. Although other deposits will be referred to, only the massive sulfide deposit of the United Verde mine will be discussed in this report.

Manuscript approved for publication February 18, 1989.

[1] Phelps Dodge Corporation, Morenci, AZ 85540.

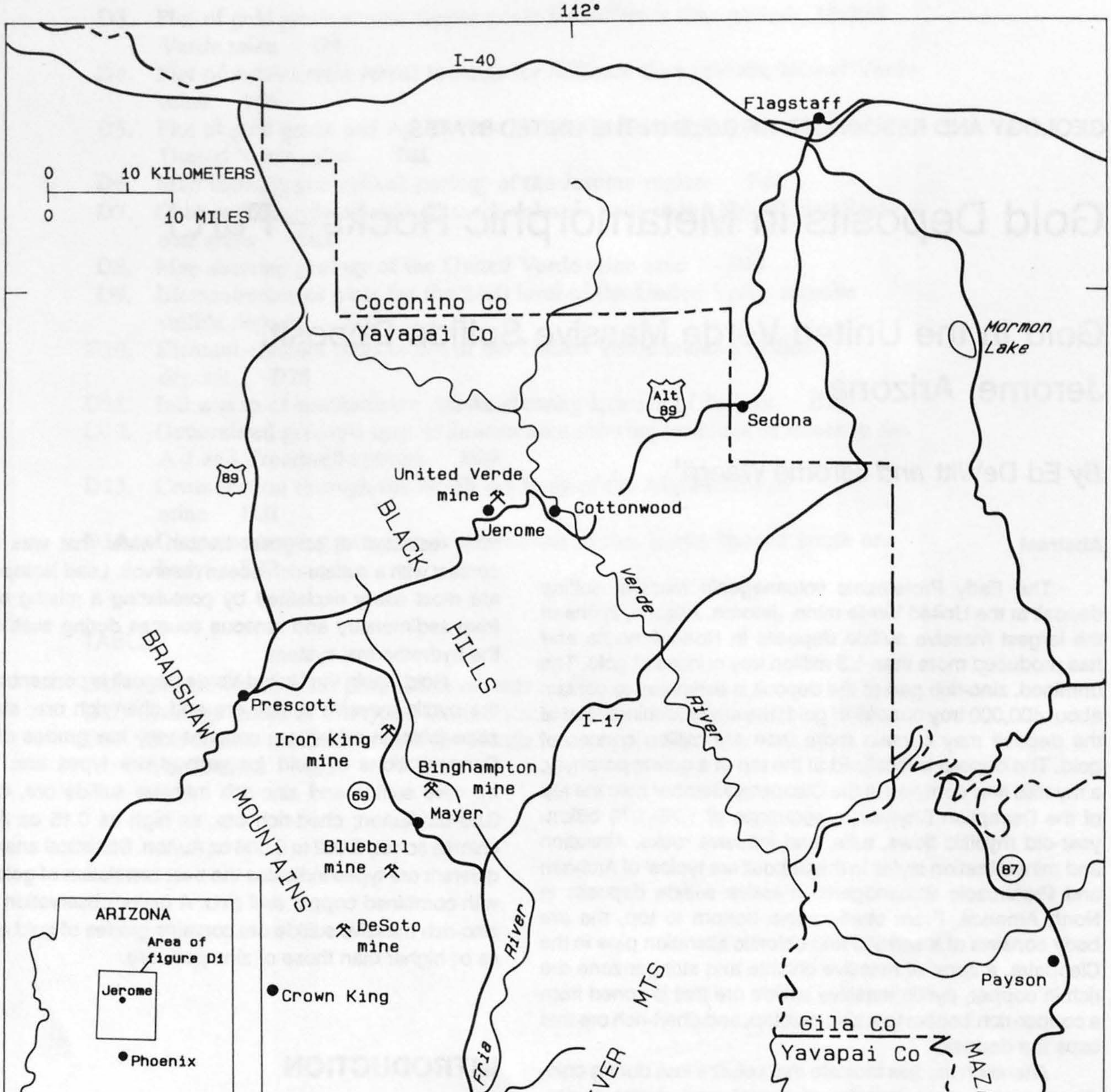


Figure D1. Location map of the Jerome area, central Arizona. Mine localities shown are mentioned in the text.

History

Prehistoric American Indians and, later, Spanish explorers in the late 1590's knew of the deposits at Jerome and recovered some copper by surface mining, but the modern history did not begin until 1876–1877 with the location of claims that would later become the holdings of the United Verde Copper Company (Hamilton, 1884; Rickard, 1918). Senator W.A. Clark of Montana purchased the United Verde holdings in 1888 and operated the United Verde mine until 1935, when Phelps Dodge Corporation purchased the property. The deposit at the United Verde mine, which consists of the mined ore and lower grade ore remaining in the ground, is the largest known massive sulfide deposit in the United States and one of the largest in North America. The mine closed in 1953, but has since been leased to several parties conducting small-scale surface mining and leaching.

Production

Production records of the Phelps Dodge Corporation indicate that from 1889 until 1974 the United Verde mine produced nearly 33,000,000 short tons of ore that yielded more than 2,921,000,000 lb of copper, 52,891,000 lb of zinc, 49,279,000 troy ounces of silver, and 1,350,000 troy ounces of gold (table D1). Unpublished data from the Arizona Bureau of Geology and Mineral Technology indicate that from 1884 through 1888 and in 1975 an additional 27,000 tons of ore was produced that yielded about 6,900,000 lb of copper, 324,000 oz of silver, and 4,200 oz of gold. Unpublished data from the same source indicate an additional 45,000,000 lb of zinc and 459,000 lb of lead were produced during the lifetime of the United Verde mine. From 1920 through 1940 the open pit operations produced 9,708,923 tons of ore that contained 674,734,000 lb of copper, 20,529,100 oz of silver, and 689,260 oz of gold (Alenius, 1930, 1968; fig. D2*A*). From 1900 through 1975 the silver grade of ore decreased from more than 4.0 oz Ag/ton to 1.0 oz Ag/ton (fig. D2*B*). During the same time gold grade decreased from approximately 0.085 oz Au/ton to 0.010 oz Au/ton, resulting in an increase of the Ag:Au ratio from 25 to 75 (fig. D2*C*). From 1884 through 1975 the ore averaged 1.49 oz Ag/ton and 0.041 oz Au/ton, and had a Ag:Au ratio of 36.3. From 1903 through 1953 the gold grade of the ore had a roughly positive correlation with copper content (fig. D3); the highest grade copper ores of 1903–1911 contained the highest gold grades, and the lowest grade copper ores of 1940–1953 contained the lowest gold grades. This correlation is partly the result of the mining of oxidized ores with high gold content early in the history of the deposit. Gold grades from 1960 through 1975 did not follow the rough positive correlation with copper content, as much of the material mined during that time was from mineralized quartz porphyry and black schist (hydrothermally altered quartz porphyry), and not from massive sulfide ore.

The Ag:Au ratio of mined ore has varied over time and with the tonnage of ore produced (fig. D4). From 1901 through 1920, Ag:Au ratios increased with increasing underground production; as tonnage increased the gold grade decreased more than the silver grade (figs. D2*A*, D2*C*). When open pit production began in 1920 and overtook underground production in 1922–1923, the Ag:Au ratio stabilized at 30–40 and was independent of tonnage produced through 1939 (fig. D4). From 1940 through 1944 the Ag:Au ratio increased to 50–70 and was inversely related to production; gold grades decreased more than silver grades (figs. D2*B*, D2*C*). When zinc production began in 1944–1945, the Ag:Au ratio stabilized at about 50 and was independent of tonnage produced. Notably, the gold grade increased slightly from 1945 through 1953 (fig. D2*C*), and zinc-rich ore contained as much gold as did copper-rich ore (fig. D5).

Because only the copper-rich part of the massive sulfide lens and surrounding rock was mined at the United Verde, a very large tonnage of low grade, probably subeconomic, ore remains in the ground. Reber (1922, 1938) estimated that only 14–20 percent of the original 90,000,000–ton body was of commercial grade (greater than 2 percent copper). Both Paul Handverger (written commun., 1974) and Paul Lindberg (written commun., 1977) estimated that the deposit contained 80,000,000 to 100,000,000 tons of mineralized material, 75 percent of which remains in the ground. If the areas indicated by Anderson and Creasey (1958, fig. 14) are used to calculate tonnages, approximately 115,000,000 tons of low-grade massive sulfide ore and 38,000,000 tons of mineralized black schist remain in the United Verde mine from the surface to the 4500 level. The grade of the massive sulfide material is unknown, but a conservative estimate, based on past production data, is 0.5–1.0 percent Cu, 2–4 percent Zn, traces of lead, 0.01–0.015 oz Au/ton, and 0.5–1.0 oz Ag/ton. McIlroy and others (1974) indicated a resource of about 25,000,000 tons of ore that averages 0.52 percent Cu, 0.90 percent Pb, 4.72 percent Zn, and 2.05 oz Ag/ton, but they gave no values for gold grade. Using a cutoff grade of 4 percent zinc, Waegli and Jonathon Duhamel (unpub. data, 1981) estimated that the 500 through 3000 levels contain nearly 21,000,000 tons of ore that averages 0.52 percent Cu, 6.6 percent Zn, 0.61 oz Ag/ton, and 0.02 oz Au/ton.

Similar Deposits

The ore in the United Verde mine is interpreted to be a stratiform syngenetic deposit associated with submarine rhyolitic volcanism and hydrothermal alteration (Anderson and Nash, 1972). The ore body and associated volcanic rocks are very similar to Archean massive sulfide deposits of the Canadian Shield (Hutchinson, 1973; Sangster, 1980; Franklin and others, 1981) and the Miocene Kuroko deposits of Japan (Ishihara, 1974). In the southwestern United States similar deposits of Proterozoic age are noted near Pecos, N. Mex. (Krieger, 1932; Riesmeyer, 1978; Robertson and

Table D1. United Verde mine production records

[Data from Phelps Dodge Corporation except as footnoted; published with permission. Unpublished production records for 1884–1888 and 1975 available only from Arizona Bureau of Geology and Mineral Technology. U.V., United Verde production; P.D., Phelps Dodge production; Big Hole, composite of various small-scale leased operations; blank, no record]

		Metals recovered				
Year	Tons mined	Lbs Cu	Lbs Zn	Oz Ag	Oz Au	Lbs Pb
1884-1888[1]	26,900	6,869,075		323,726	4,242	
1889	10,000	1,910,890		154,260	9,697.5	
1890	26,000	5,257,421		423,714		
1891	37,000	7,360,000				
1892	50,000	9,845,666		109,878	2,442.7	
1893	50,000	9,222,141				
1894	58,990	11,043,542		276,258	7,778.8	
1895	60,201	16,522,181		263,080	4,627.9	
1896	116,994	22,366,425				
1897	151,266	31,355,027		526,114	9,773.6	
1898	219,831	42,453,316				
1899	254,138	43,995,733		486,470	13,956.7	
1900	245,352	39,888,472		523,723	15,943	
1901	248,646	34,438,441		504,277	15,695	
1902	133,219	19,407,080		306,784	9,551	
1903	156,970	23,771,597		450,603	15,038	
1904	268,412	29,274,610		668,612	23,762	
1905	273,523	32,683,951		486,041	15,915	
1906	274,181	38,836,441		428,317	12,913	
1907	253,566	33,015,457		356,939	11,734	
1908	241,915	36,183,089		494,574	20,334	
1909	280,534	36,695,455		495,477	17,021	
1910	323,569	38,663,880		563,132	19,267	
1911	304,949	33,164,520		461,168	15,239	
1912	351,817	31,570,152		480,518	15,069	
1913	395,674	35,344,694		641,074	20,666	
1914	397,227	32,448,170		646,573	21,400	
1915	491,992	45,127,832		903,051	28,221	
1916	694,053	58,299,573		1,030,851	26,416	
1917	813,176	71,726,634		1,223,310	29,230	
1918	861,250	77,501,595		1,292,109	29,281	
1919	469,353	42,927,666		665,327	16,838	
1920	718,851	64,952,270		910,345	18,759	
1921	132,353	13,581,488		202,716	4,090	
1922	423,543	40,845,407		554,587	12,603	
1923	1,101,456	97,560,882		2,113,162	67,541	
1924	1,257,714	98,246,081		1,846,621	48,235	
1925	1,289,350	108,210,901		2,108,348	50,196	
1926	1,285,461	107,388,418		2,242,788	55,906	
1927	1,352,387	99,969,654		2,096,681	55,897	
1928	1,580,312	118,151,126		2,113,174	55,395	
1929	1,800,607	142,290,460		2,092,418	62,096	
1930	941,196	70,720,014		1,413,333	42,938	
1931	229,789	19,891,777		309,650	10,350	
1935 U.V. through 2/18	58,546	4,679,333		66,954	2,154	
1935 P.D. from 2/19	725,020	59,817,830		867,390	27,337	
1936	1,302,974	91,514,608		1,826,875	64,531	
1937	1,433,330	85,290,903		1,907,898	65,743	
1938	772,527	55,579,814		1,040,611	41,877	
1939	740,022	55,417,033		920,091	25,652	
1940	795,784	68,111,011		917,950	17,984	
1941	1,078,462	80,858,441		1,314,725	26,649	
1942	1,212,933	86,554,613		1,279, 650	24,011	
1943	882,214	68,192,842		934,927	16,362	
1944	502,247	52,774,095		547,873	8,100	
1945	377,579	39,228,810		463,540	8,475	
1946	336,197	31,485,167		414,387	8,055	

Table D1. United Verde mine production records—Continued

Year	Tons mined	Metals recovered Lbs Cu	Lbs Zn	Oz Ag	Oz Au	Lbs Pb
1947	346,311	31,063,468		391,993	7,573	
1948	348,048	29,833,400		436,721	11,166	
1949	409,313	33,957,890	8,005,488	485,301	9,497	
1950	351,992	15,426,569	15,157,169	272,342	6,117	
1951	299,436	19,830,228	17,915,943	399,689	7,000	
1952	155,642	10,475,722	9,613,749	249,015	4,300	
1953 End P.D.	29,164	1,938,803	2,199,620	49,058	1,258	
---- Start						
1954 Big Hole	5,004	605,319		3,604	31.5	
1955	13,447	1,371,056		9,453	77.7	
1956	14,929	1,545,434		10,843	84.0	
1957	12,872	1,644,400		14,773	333.8	
1958	16,010	2,067,960		27,724	586.7	
1959	9,824	969,108		9,627	290.7	
1960	17,010	2,299,801		10,088	101.9	
1961	18,533	2,436,505		16,187	143.2	
1962	10,477	1,770,601		8,794	113.8	
1963	15,076	2,326,437		13,414	179.1	
1964	8,203	876,828		7,974	105.1	
1965	9,577	1,216,466		9,603	152.3	
1966	5,552	543,943		4,174	54.9	
1967	5,006	528,227		3,751	50.1	
1968	5,218	565,219		5,649	68.6	
1969	9,299	1,118,820		9,950	100.8	
1970	11,062	1,392,423		12,946	155.7	
1971	7,238	758,239		8,428	110.1	
1972	6,214	615,609		6,732	69.8	
1973	1,705	173,120		1,829	19.3	
1974	3,923	376,019		4,190	48.6	
1975[1]	598	91,292		654	6.0	
Total U.V.	20,685,383	1,978,768,862		34,360,185	971,801	
Total P.D.	12,099,195	917,312,277	52,891,969	14,720,036	381,687	
Total Big Hole	206,150	25,201,534		199,793	2,877.7	
Grand Total[2]	32,990,728	2,921,291,673	52,891,969	49,279,954	1,356,366	
ABGMT[3]	33,018,255	2,928,252,040		49,604,334	1,360,614	459,100
ABGMT Total[4]	32,588,782	2,844,403,043	97,352,100	49,732,425	1,376,108	459,100

[1] Includes data from Arizona Bureau of Geology and Mineral Technology (ABGMT).
[2] Excludes data from ABGMT.
[3] Includes 1884-1888, 1975 data from ABGMT.
[4] Total from records of ABGMT.

Moench, 1979), and in central and western Arizona (Anderson and Guilbert, 1979; Gilmour and Still, 1968; DeWitt, 1979; Baker and Clayton, 1968; Anderson and others, 1955; Stensrud and More, 1980; and Donnelly and Hahn, 1981). In central and western Arizona similar but smaller volcanogenic massive sulfide deposits include the Iron King, Zonia, United Verde Extension, Old Dick–Bruce, Bluebell, Copper Chief, Desoto, and numerous much smaller deposits.

Acknowledgments

Phelps Dodge Corporation contributed unpublished production data and assay results from the 2400 level of the United Verde mine. Anna Wilson aided in the computer plotting of the data from Storms (1955). The manuscript was reviewed by Phillip Anderson, Jonathon Duhamel, Gary Landis, and D.M. Sheridan, and benefited from their comments.

GEOLOGY

Stratified Metavolcanic and Metasedimentary Rocks

The United Verde massive sulfide deposit lies at the top of a sequence of interbedded rhyolitic to basaltic

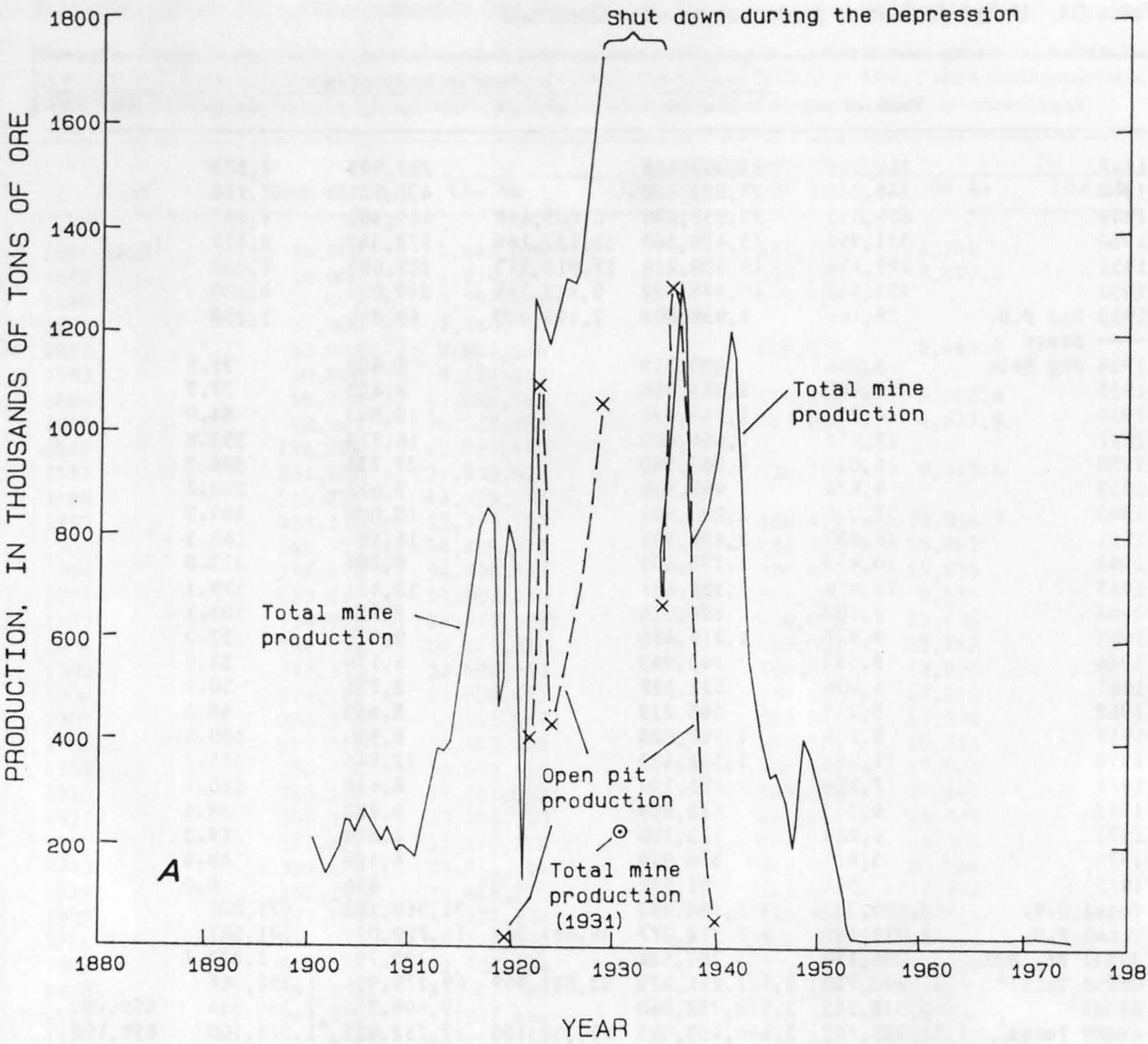


Figure D2 (above and following pages) . Data for the lifetime of the United Verde mine. Data are from table D1, and unpublished data from the Arizona Bureau of Geology and Mineral Technology. *A*, plot of production versus time. *B*, plot of copper and silver grades versus time. *C*, plot of Ag:Au and gold grade versus time. Dashed lines between X's in *A* connect data for intermittent years; dashed curves in *B* and *C* are average trends.

volcanic rocks which have been metamorphosed to lower greenschist facies. Mixed sedimentary and volcaniclastic rocks overlie the massive sulfide deposit. Because original volcanic textures and structures are well preserved and deformation has not obliterated stratigraphic relations, the metamorphosed lithologies will be described by their protoliths. Detailed stratigraphy was described in Anderson and Creasey (1958) and Anderson and Nash (1972).

According to data in Anderson and Creasey (1958), volcanic rocks older than the massive sulfide deposit are a bimodal suite of basalt and basaltic andesite (40 percent) and rhyolite (55 percent), with only minor amounts (5 percent) of andesite and dacite (fig. D6). The mafic rocks include the Gaddes Basalt and Shea Basalt, both of which are pillow lava flows with minor tuff and rhyolite breccia beds. The intermediate rocks are represented only by the Brindle Pup Andesite, a flow unit containing intercalated basalt and rhyolite flows. The felsic rocks include the Buzzard Rhyolite, dacite of Burnt Canyon, and Deception Rhyolite and allied minor intrusive rocks. These felsic extrusive units consist of flows, flow breccias, jasper-rich flows, and crystal and lithic tuffs. Porphyritic rhyolite (Cleopatra Quartz Porphyry) once thought to intrude the Deception Rhyolite (Reber, 1922; Anderson and Creasey, 1958) is now included as the Cleopatra Member, an extrusive unit within the Deception (Anderson and Nash, 1972).

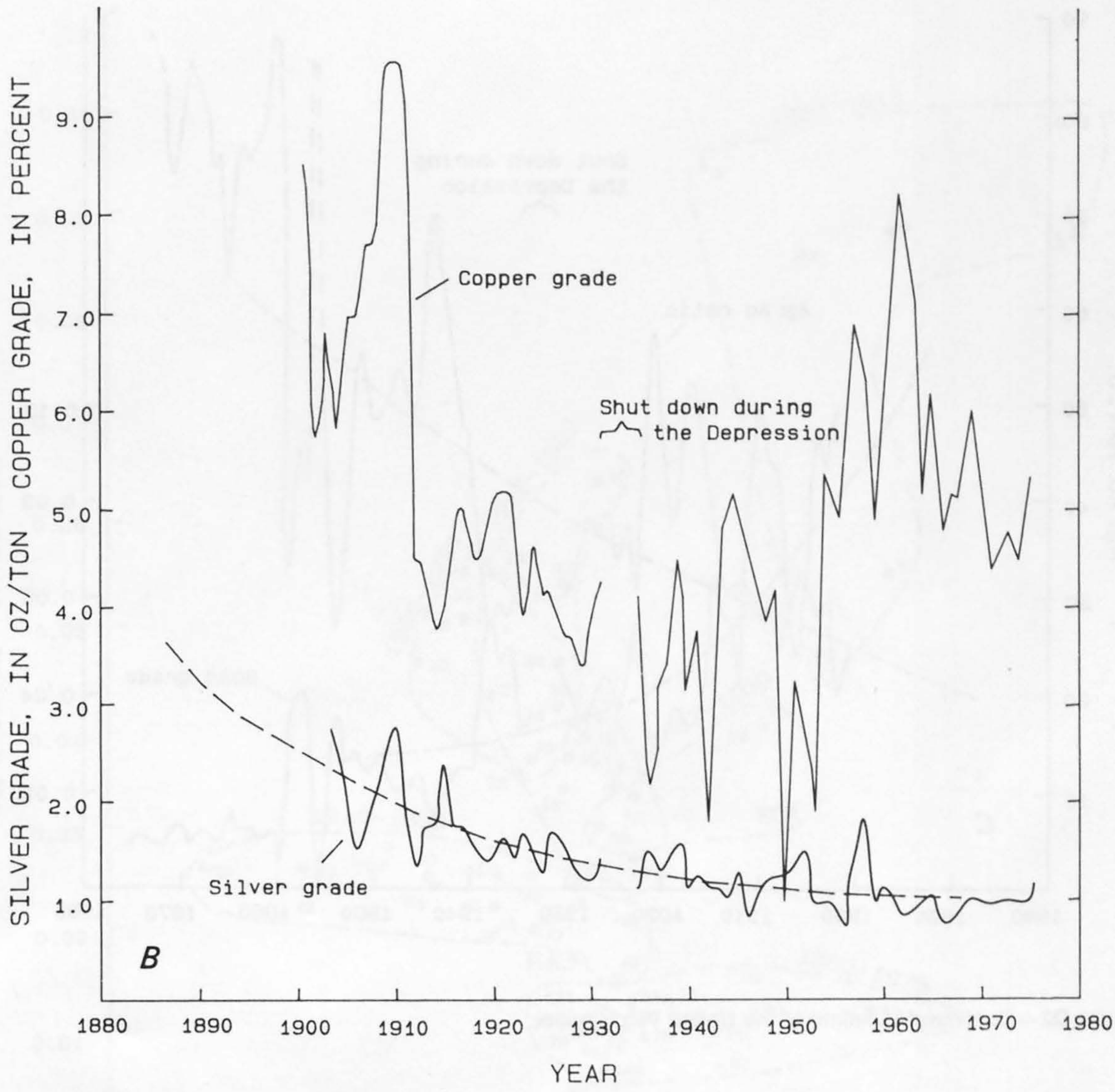


Figure D2—Continued. Lifetime of the United Verde mine.

The analytical data for 11 unaltered metavolcanic rocks in the Jerome area (Anderson and Creasey, 1958), however, do not indicate such a bimodal suite. (See discussion in DeWitt and Waegli, 1986.) A chemical classification of these rocks (fig. D7), based on the major element method of De la Roche and others (1980), indicates a gradational range of compositions from rhyolite to basalt instead of the bimodal suite of rhyolite and basalt-basaltic andesite. The major-element chemistry of unaltered volcanic units in the Jerome area is similar to that in the Prescott area to the west (fig. D7) where calc-alkalic, iron-rich, low- to medium-potassium rocks predominate (DeWitt and Waegli, 1986).

Volcanic rocks that predate the ore deposit are predominantly calc-alkalic (Peacock, 1931), as shown on figure D7. The Shea and Gaddes Basalts are low-potassium rocks and the rest of the units are either low- or medium-potassium rocks according to the classification of Peccerillo and Taylor (1976). The suite is predominantly metaluminous (Shand, 1927), but felsic rocks are slightly peraluminous due to alkali depletion related to hydrothermal alteration near ore bodies. All the volcanic units that predate the ore deposit are iron-rich (Miyashiro, 1974). Magnesium-rich rocks are noted only in hydrothermally altered areas near ore bodies.

Metasedimentary and metavolcanic units that were deposited with or postdate the massive sulfide deposit include coarse- and fine-grained tuffaceous rocks, volcanic breccia, chert and jasper beds, and dacite and andesite of the Grapevine Gulch Formation (Anderson and Creasey, 1958; Anderson and Nash, 1972). Chemically the dacite in the Grapevine Gulch is an

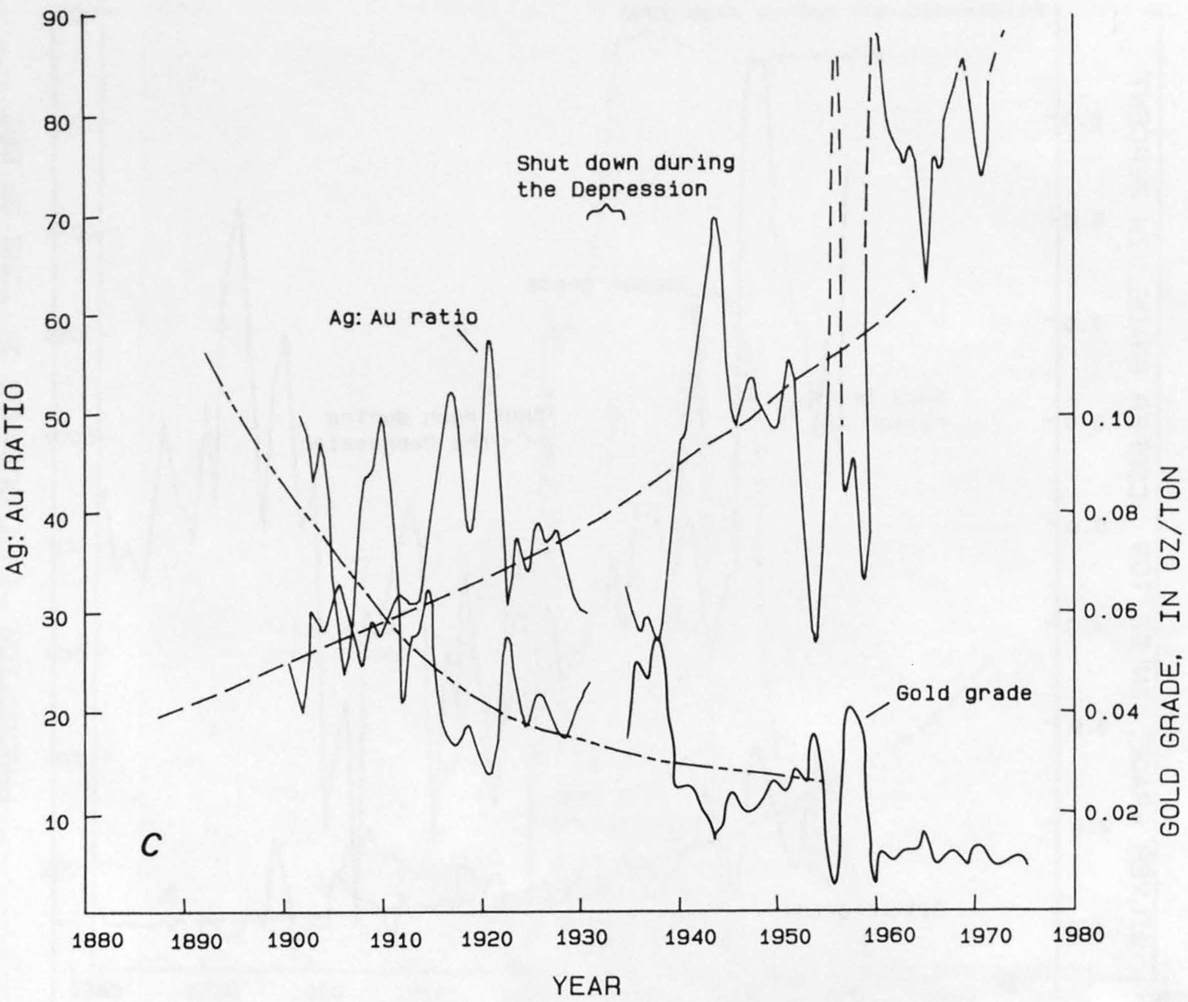


Figure D2—Continued. Lifetime of the United Verde mine.

alkali-calcic rhyolite, unlike older calc-alkalic units in the Jerome area (fig. D7). Crystal tuffs are locally abundant in the upper part of the Grapevine Gulch Formation, indicating that rhyolitic volcanism continued after deposition of tuffaceous rocks, minor limestone, and some agglomerate (Reber, 1922). Breccia beds in the basal Grapevine Gulch contain mineralized fragments of Deception Rhyolite (Anderson and Nash, 1972). However, a change in style of alteration within rocks of the upper part of the Cleopatra led Gustin (1986, 1987) to suggest that the time horizon represented by the massive sulfide deposit is within the Cleopatra, not at the overlying contact with the rocks of the Grapevine Gulch.

Volcanic rocks associated with the United Verde deposit have been described as having formed in a greenstone belt (Anderson and Silver, 1976), and in volcanic arcs with distinct polarities and chemical evolution (Anderson, 1978). Vance and Condie (1986) suggested that the volcanic rocks formed in a combination of arc and back-arc settings.

Intrusive Rocks

All pre-ore metavolcanic and metasedimentary units have been intruded by minor quartz porphyry dikes, a large gabbro body (United Verde Diorite of Reber, 1922), and later andesite(?) porphyry dikes. In the southern part of the Jerome area, a quartz diorite pluton (Anderson and Creasey, 1967) intrudes those units. The age of the pluton is 1,740±15 Ma (Anderson and others, 1971; date recalculated using decay constants in Steiger and Jaeger, 1977). The gabbro in the United Verde mine area was intruded as a sill near the contact of the Grapevine Gulch Formation and Cleopatra Member of the Deception Rhyolite, and locally it cut out and isolated pieces of the massive sulfide deposit (Haynes ore body; pl. 7 and fig. 24 of Anderson and Creasey, 1958; pl. X of Reber, 1938; Anderson and Nash, 1972). The gabbro is not foliated as extensively as the rocks it intrudes, but it has been metamorphosed to the same degree as the stratified rocks. Chemically, the gabbro has been

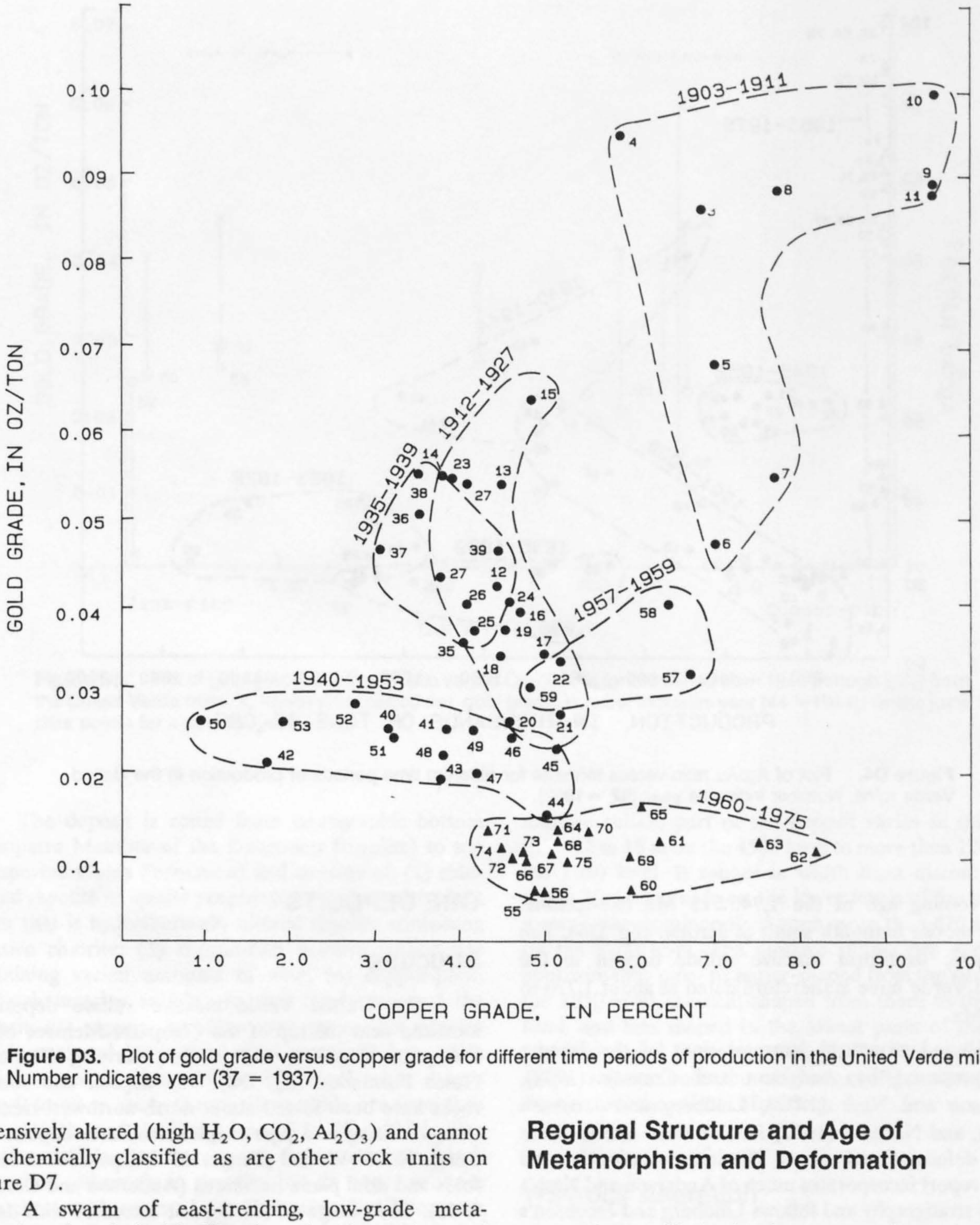


Figure D3. Plot of gold grade versus copper grade for different time periods of production in the United Verde mine. Number indicates year (37 = 1937).

extensively altered (high H_2O, CO_2, Al_2O_3) and cannot be chemically classified as are other rock units on figure D7.

A swarm of east-trending, low-grade metamorphosed andesite(?) dikes intrudes the gabbro and massive sulfide lens in the United Verde mine (Provot, 1916; Reber, 1922). The dikes are undeformed, but they do contain sparse pyrite and chalcopyrite (Anderson and Creasey, 1958). Apparently the dikes were emplaced after regional deformation ceased, and the heat from the dikes caused very local remobilization of sulfide minerals.

Regional Structure and Age of Metamorphism and Deformation

The stratified volcanic sequence that underlies the massive sulfide deposit has a minimum age of 1,770 to 1,780 Ma, which is the U-Pb zircon age of the Cleopatra Member of the Deception Rhyolite (L.T. Silver, written commun., 1982). Regional deformation and low-grade metamorphism of this 1,770–1,780 Ma sequence, and the younger Grapevine Gulch Formation and gabbro, occurred between 1,770 Ma and 1,690 Ma, which is the

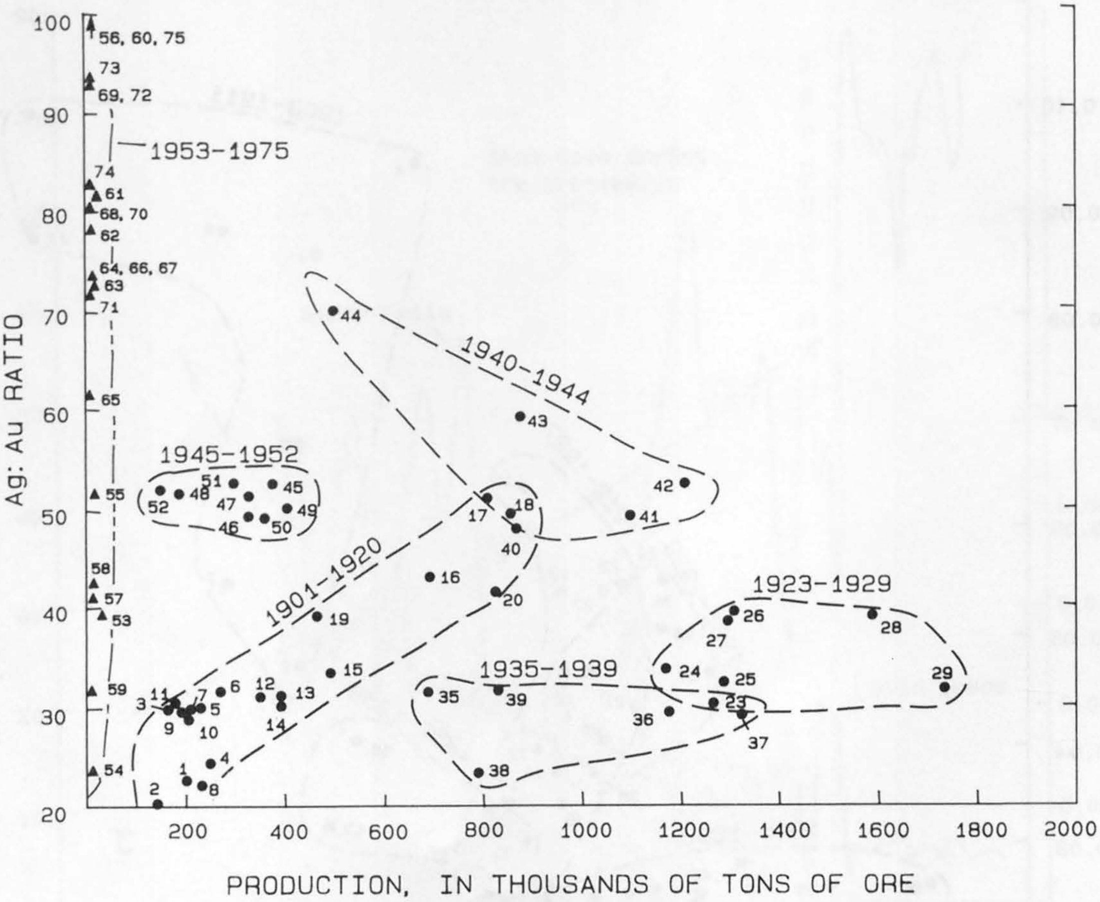


Figure D4. Plot of Ag:Au ratio versus tonnage for different time periods of production in the United Verde mine. Number indicates year (52 = 1952).

K-Ar cooling age of the 1,740±15 Ma late-tectonic quartz diorite batholith south of Jerome (fig. D6). The syngenetic stratiform massive sulfide deposit in the United Verde mine is therefore dated at about 1,770 to 1,780 Ma.

Varied structural interpretations of the Jerome area proposed by Anderson and Creasey (1958), Anderson and Nash (1972), Lindberg and Jacobsen (1974), and Norman (1977) involve from one to three major deformational events. The interpretation favored in this report incorporates much of Anderson and Nash's (1972) stratigraphy and follows Lindberg and Jacobsen's (1974) model for two generations of folding (figs. D6 and D8). In the area south of Jerome, the northwest-trending Jerome anticline (F_1, fig. D6) has been crossfolded about west-northwest-trending axes. The regional foliation in the metamorphosed lithologies parallels the second generation of folds (F_2, fig. D6). Locally, as near the United Verde mine, F_1 and F_2 structural features are parallel and the effects of refolding are not apparent.

ORE DEPOSITS

Structure

The United Verde massive sulfide deposit is localized near the top of the Cleopatra Member of the Deception Rhyolite, and in the overlying Grapevine Gulch Formation (fig. D8). The deposit and country rocks have been folded about north-northwest-trending axes, resulting in a pipe-shaped stratiform deposit that trends N. 20° W. and plunges 65° N., parallel to minor folds and axial plane lineations (Anderson and Creasey, 1958). The plunge of the deposit increases with depth. Above the 1100 level the plunge averages 45°; from the 1100 level to the 3300 level it averages 70°; and from the 3300 level to the 4500 level it is vertical or reverses plunge to the southeast. A sill-like body of gabbro which isolates and cuts off parts of the top of the ore body (see pls. 7 and 10 of Anderson and Creasey, 1958) was emplaced along the contact between the Cleopatra Member and the Grapevine Gulch Formation.

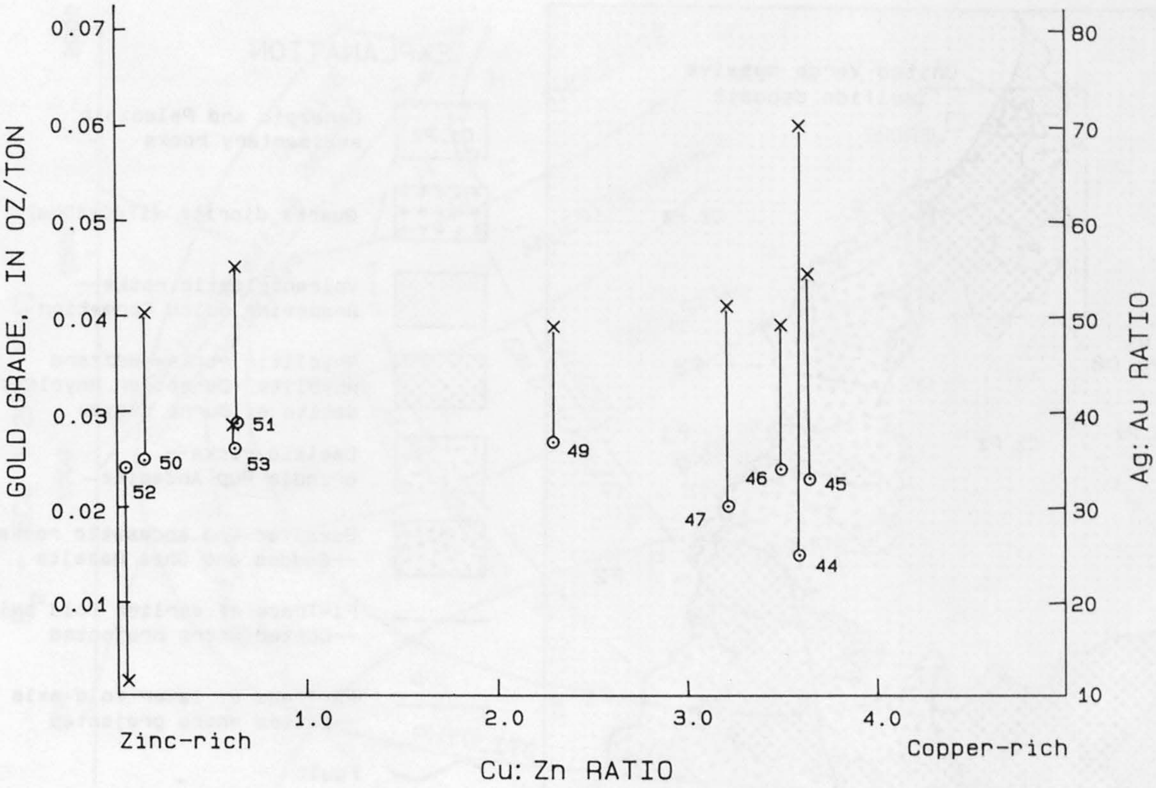


Figure D5. Plot of gold grade and Ag:Au ratio versus Cu:Zn ratio for ore mined from 1944 through 1953 from the United Verde mine. X, Ag:Au ratio; circled dot, gold grade; number indicates year (44 = 1944); tie line joins data points for a specific year.

The deposit is zoned from stratigraphic bottom (Cleopatra Member of the Deception Rhyolite) to top (Grapevine Gulch Formation) and consists of: (1) chloritized rhyolite or quartz porphyry; (2) copper-rich black schist that is hydrothermally altered rhyolite containing massive chlorite; (3) copper-rich massive sulfide ore containing varied amounts of zinc; (4) copper-poor, zinc-rich massive sulfide ore that forms most of the deposit; (5) copper- and zinc-poor, pyrite-rich massive sulfide ore; and (6) jaspery chert lenses (Reber, 1922; Anderson and Creasey, 1958). The black schist ranges from 0 to 60 m thick, the massive sulfide ore from 0 to 120 m thick, and the chert from 0 to 40 m thick. The massive sulfide deposit grades downward into black schist and ultimately to rhyolite, but its upper contacts with chert, with rocks of the Grapevine Gulch, or with rhyolite are sharp. Laterally, the massive sulfide grades into and is interbedded with rhyolite and rocks of the Grapevine Gulch.

The sulfide mass is exposed from the surface to the 4500 level of the mine, and undoubtedly once extended upward to the overlying Cambrian Tapeats Sandstone, an additional vertical distance of about 120 m. The sulfide body therefore had a minimum length of 1,600 m. The massive sulfide part of the deposit varies in thickness from 12 to 18 m on the 4500 level to more than 120 m on the 1650 level. It ranges in width from discontinuous zones 75–160 m wide on the lower levels of the mine to a continuously mineralized zone more than 420 m wide on the 3000 level. The massive sulfide ore deposit is approximately pipe- or molar-shaped from the surface to the 1650 level, crescent-shaped from there to the 3300 level, and lens-shaped in the lowest parts of the mine (Anderson and Creasey, 1958, pl. 7). This variation in shape reflects both the original configuration of the deposit and the effects of folding.

Wallrock Alteration

Both the Cleopatra and tuffaceous units of the Grapevine Gulch Formation below and adjacent to the massive sulfide lens have been variably chloritized and sericitized (Anderson and Creasey, 1958). Chloritization of rhyolite by the action of hot seawater brine converted rhyolite to black schist in the mine area (Anderson and Nash, 1972). Regionally, sericitization of the rhyolite was

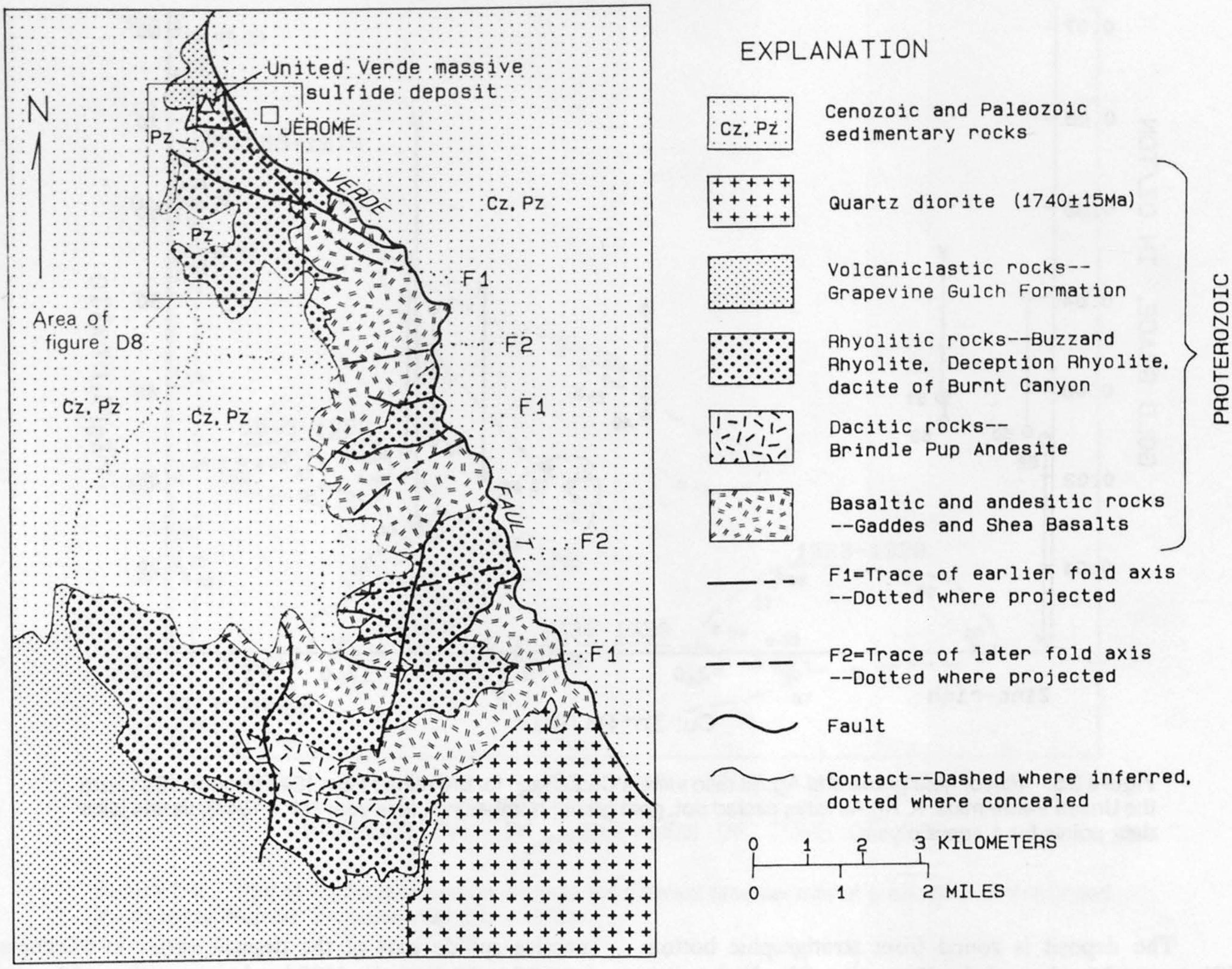


Figure D6. Generalized geology of the Jerome region. Modified from Anderson and Creasey (1958). Mapped units listed by rock type rather than by age.

more widespread than chloritization, but it was not as pervasive and it may not have been related entirely to the ore-forming process. Instead, some of the sericite may represent premetamorphic devitrification and alteration of glass and pumice within the rhyolitic units (Anderson and Creasey, 1958). Microprobe analyses indicate that chlorite in the black schist from the United Verde mine is ripidolite (classification of Hey, 1954) with an Fe:Fe+Mg ratio that ranges from 0.37 to 0.49 (Nash, 1973). Chlorite of this composition is classified as prochlorite (Saggerson and Turner, 1982). The magnesium content of the ripidolite in the Cleopatra increases south to north toward the United Verde mine. Similar magnesium-rich chlorite (Fe:Fe+Mg ratio of 0.31–0.56) has been reported from the alteration pipe of the Bruce massive sulfide deposit near Bagdad, Ariz. (Larson, 1984, 1987).

Many major, minor, and trace elements have been mobilized within the chloritic and sericitic alteration zones. In massive chlorite or black schist zones, SiO_2, Na_2O, CaO, K_2O, rubidium, strontium, and barium show depletion relative to least altered rhyolitic rocks (Vance and Condie, 1987). SiO_2 and K_2O show the greatest relative depletion. Chloritized zones show relative enrichment of MgO, Al_2O_3, volatile constituents, total iron, cesium, uranium, thorium, manganese, scandium, cobalt, rare-earth elements (especially the light rare-earths), zirconium, niobium, yttrium, tantalum, and hafnium. Some of this apparent enrichment is due to volume loss during alteration of the rhyolite, but much enrichment is due to mass transfer of constituents in the hydrothermal system. In zones characterized by sericitic alteration, Na_2O and CaO are depleted relative to least altered rhyolite, and MgO, SiO_2, total iron, volatile

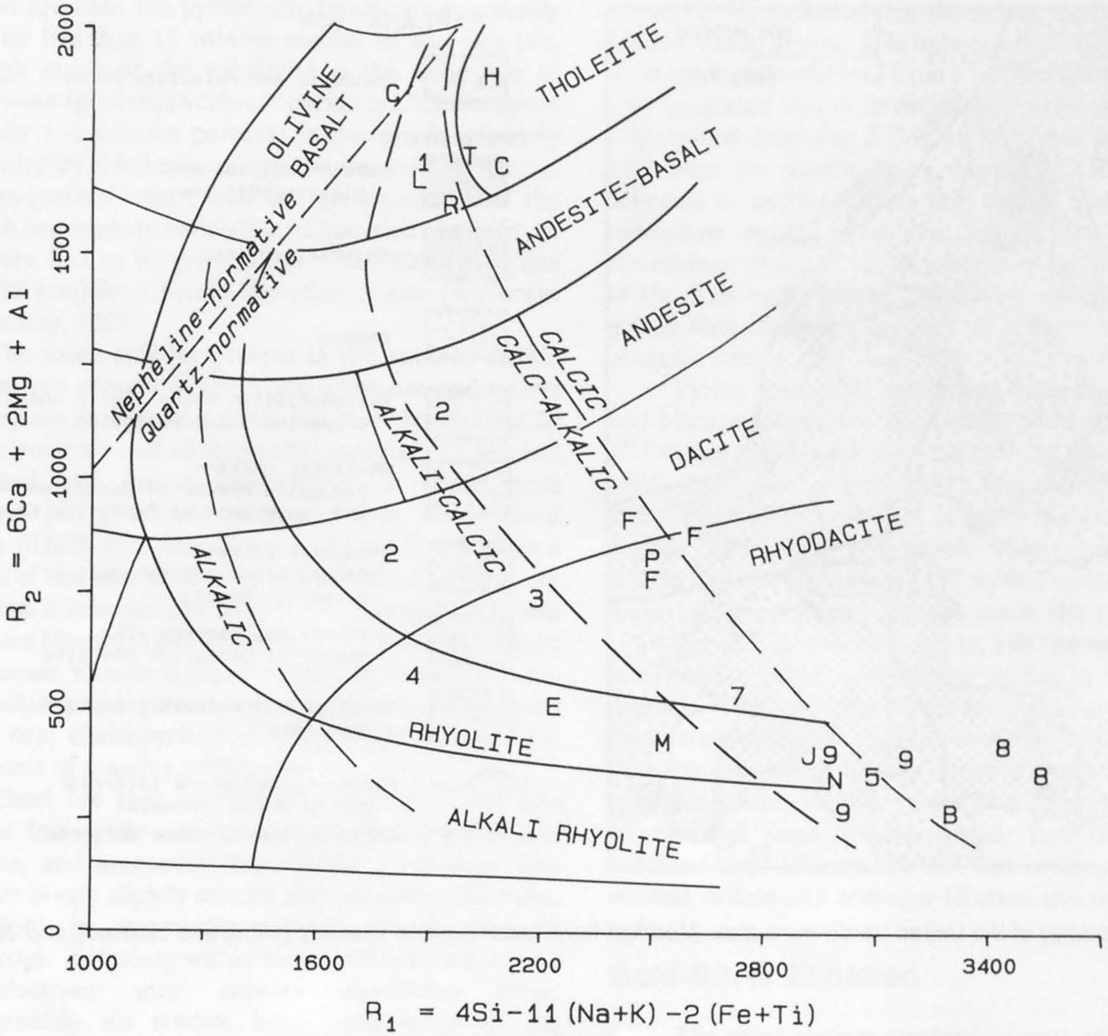


Figure D7. Chemical classification diagram (De la Roche and others, 1980) for volcanic units in the Jerome and Prescott areas. Data from Anderson and Creasey (1958), Anderson and Blacet (1972), Krieger (1965), and Vrba (1980). Only those analyses (in weight percent) are plotted that contain less than 3.0 percent H_2O and less than 1.0 percent CO_2, and that have total oxide weight percents between 98.5 and 100.5 percent. Numbers designate rock units in the Jerome area: 1, gabbro at United Verde mine; 2, Shea Basalt; 3, Brindle Pup Andesite; 4, dacite from Grapevine Gulch Formation; 5, Buzzard Rhyolite; 7, dacite of Burnt Canyon; 8, Cleopatra Member; 9, other quartz porphyries probably correlative with Cleopatra. Letters designate rock units in the Prescott area: B, rhyolite near the Binghampton mine; C, basalt east of the DeSoto mine; E, rhyolite southwest of Iron King mine; F, andesite northwest of DeSoto mine; H, basalt south of Iron King mine; J, rhyolite south of Binghampton mine; L, basalt near Bluebell mine; M, rhyolite north of Bluebell mine; N, rhyolite northeast of Iron King mine; P, andesite southwest of Iron King mine; R, basalt near Binghampton mine; T, basalt east of DeSoto mine. Approximate boundaries between calcic, calc-alkalic, alkali-calcic, and alkalic suites shown by heavy, dashed lines.

constituents, and locally K_2O are enriched. Light-ion lithophile elements, rare-earth elements, and high-field-strength elements are not measurably enriched or depleted to the levels of those elements in least altered rhyolite in sericitic zones (Vance and Condie, 1987).

On the basis of alteration studies, Vance and Condie (1987), Gustin (1986, 1987), and Lindberg and Gustin (1987) suggested that the contact at the top of the Cleopatra Member, not the contact between the upper unit of the Deception Rhyolite and the Grapevine Gulch Formation, marks the time horizon of massive sulfide deposition. At the inferred time horizon, chloritized and sericitized rocks are overlain by hematite-rich and carbonate mineral- and epidote-bearing assemblages that contain lesser amounts of sericite and chlorite (Gustin, 1987). Also, chlorite from the hematite-rich rocks is

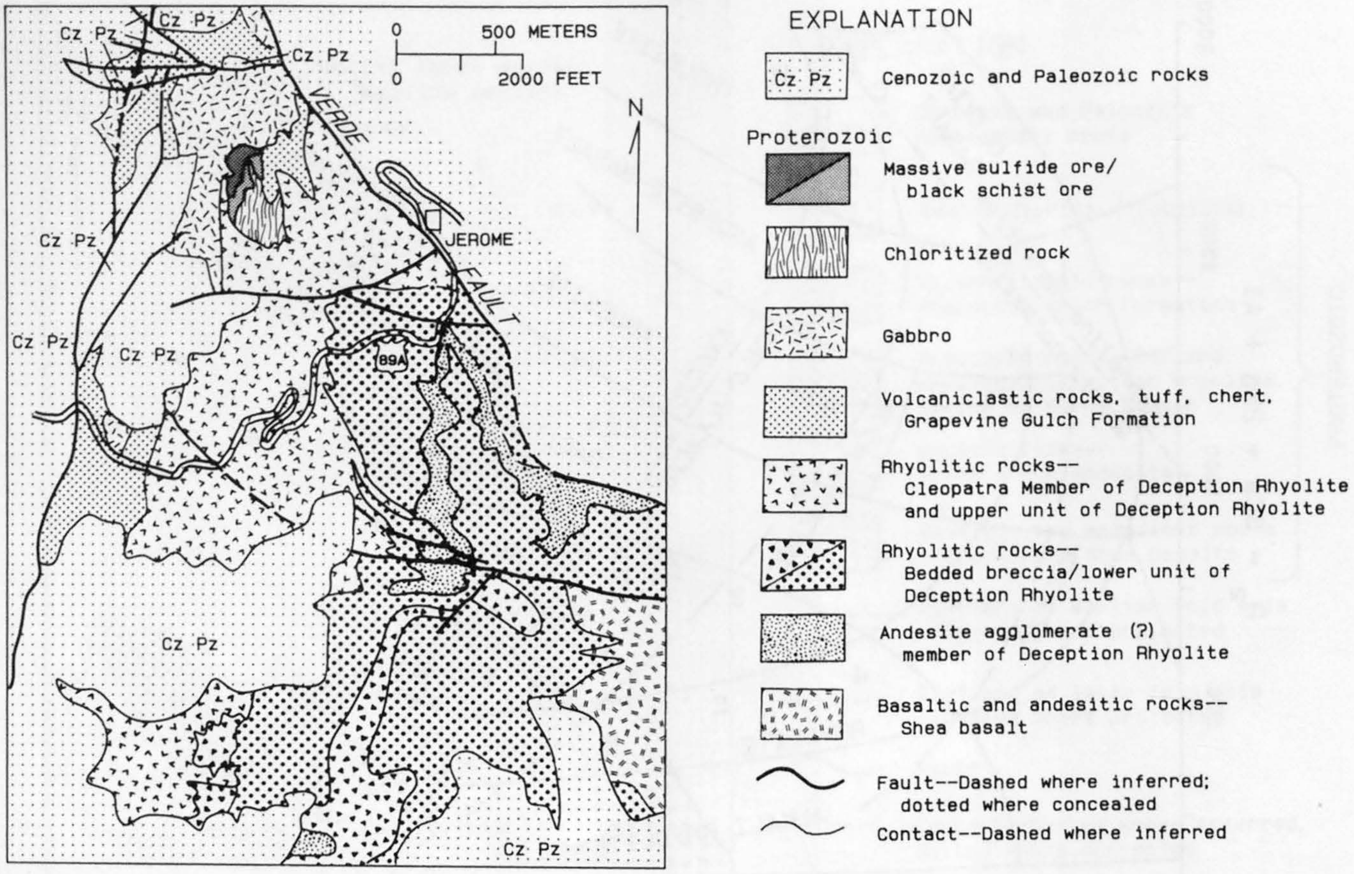


Figure D8. Geology of the United Verde mine area. Modified from Anderson and Creasey (1958) and Lindberg and Jacobsen (1974).

more iron rich than the prochlorite reported from beneath the deposit. In addition, hematite-rich rocks contain recognizable feldspar phenocrysts, whereas the chlorite-rich rocks have no preserved feldspar phenocrysts (Gustin, 1986, 1987), suggesting that a significant change in volcanic activity took place at the horizon of the United Verde massive sulfide deposit.

Mineralogy

The primary mineralogy of the United Verde massive sulfide deposit is simple, and it has been modified by weathering or supergene processes. Naturally oxidized (weathered) ores above the 160 level and ores oxidized by mine fires down to the 600 level contained cuprite, chalcocite, azurite, malachite, native copper, wire silver, minor copper hydroxide minerals, limonite, and hydrous copper sulfate minerals (Reber, 1922; Lindgren, 1926; Anderson and Creasey, 1958).

Ore minerals in the massive sulfide lens are, in decreasing order of abundance, pyrite, sphalerite, chalcopyrite, bornite, arsenopyrite, galena, tennantite, and gold (probably electrum). Gangue minerals include quartz, carbonate minerals, chlorite, sericite, and minor hematite. Pyritic massive sulfide ore typically averages about 50–60 percent sulfide minerals, is nonbanded, fine grained (0.04–0.2 mm diameter range; 0.1 mm diameter average), and consists of pyrite, minor sphalerite and chalcopyrite, very minor arsenopyrite, and interstitial quartz and carbonate minerals, chiefly dolomite and ankerite (Lindgren, 1926; Ralston, 1930; Slavin, 1930; Anderson and Creasey, 1958). Sulfide minerals other than pyrite typically make up less than 5 volume percent of the pyritic massive sulfide ore. Basal parts of massive sulfide ore contain local concentrations of chlorite-rich ore.

Zinc-rich massive sulfide ore typically is more banded than pyritic massive sulfide ore and consists of alternating zinc- and pyrite-rich layers about one-quarter inch thick (Anderson and Creasey, 1958). Sphalerite in the ore is light brown and contains about 6.5 percent iron. The amount of sulfide minerals relative to gangue minerals is about the same as in pyritic massive sulfide ore, but carbonate minerals form less of the zinc-rich ore than the pyritic ore. Sphalerite commonly makes up less than 15 volume percent of zinc-rich ore. Although much of the sphalerite is the same age as pyrite, some sphalerite veins cut pyritic ore. Chalcopyrite (normally 1–2 volume percent) in the ore is generally surrounded by sphalerite, as are minute grains of galena. The fine-grained nature and intergrown texture of the zinc-rich ore made beneficiation of zinc-rich ore difficult, as the ore had to be ground finer than 300 mesh (less than 0.02 mm) for efficient liberation of zinc (Anderson and Creasey, 1958).

The same sulfides present in the massive sulfide lens also are present in the black schist ore and quartz porphyry ore, but pyrite is much less abundant (about 20 volume percent) and chalcopyrite, especially in veinlets associated with quartz and chlorite, is much more abundant (7–15 volume percent). Very fine grained chlorite (0.002–0.01 mm diameter) forms 30–65 volume percent of the ore. Quartz is less abundant in both ore types than it is in massive sulfide ore. Zircon (relict from Cleopatra Member) and rutile (hydrothermal?) are trace constituents. Bornite is present locally in black schist ore. Black schist ore, in places, appears to grade into massive sulfide ore; chalcopyrite-rich veinlets typically cut the basal parts of massive sulfide ore.

Chert ore that overlies the massive sulfide lens contains less pyrite and more chalcopyrite, sphalerite, hematite, and magnetite than do the other ores. The chert ore is very slightly coarser than massive sulfide ore.

Gold is apparently present as electrum in microscopic inclusions within most sulfide minerals, and the electrum may contain significant silver. Unfortunately no studies have been made of the mineralogy or occurrence of gold and silver. Much silver is present in late-stage tennantite in quartz-carbonate veins and carbonate-rich massive sulfide ore (Anderson and Creasey, 1958, table 16). This tennantite contains significant gold also, most probably as microscopic inclusions.

Lead and Sulfur Isotope Data

Galena from the United Verde deposit was first analyzed for lead isotope ratios by Mauger and others (1965), who reported a 1,767 Ma single-stage model lead date (date recalculated using data in Appendix C, Doe and Stacey, 1974) for the apparently conformable base metal deposit. Subsequently, Stacey and others (1976) reported galena from the deposit to have the following lead isotopic ratios: $^{206}Pb/^{204}Pb = 15.725$; $^{207}Pb/^{204}Pb = 15.270$; $^{208}Pb/^{204}Pb = 35.344$. A single-stage model lead date calculated for this galena, again using data in Doe and Stacey (1974), is 1,729 Ma, but the point falls slightly off the single stage growth line on a $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram. Stacey and others (1976) indicated that the galena analysis from the United Verde deposit falls between their curves for lead from the mantle and lead from a well-mixed orogene, and they suggested that their two-stage model isochron date (Stacey and Kramers, 1975) of 1,645 Ma is a result of lead from the mantle being mixed with lead from an orogenic or marine source that was of a slightly more radiogenic nature than the mantle lead. The age discrepancy of about 130 m.y. between the preferred age of the host rocks (about 1,775 Ma) and the two-stage galena date likely is a function of isotopic mixing in an orogenic setting.

Pyrite, sphalerite, and galena from massive sulfide and black schist ore in the United Verde deposit have $\delta^{34}S$ values that range from –2.8 to +0.2 per mil (Gustin, 1986; Eastoe and others, 1987). The restricted range of $\delta^{34}S$ from sulfide minerals in both the United Verde deposit and other Proterozoic volcanogenic massive sulfide deposits in Arizona (127 sulfide minerals from all major and most minor deposits are in the range –2.0 to +3.2 per mil; Eastoe and others, 1987) contrasts with a much wider range and heavier sulfur in Phanerozoic deposits. The restricted range for Proterozoic volcanogenic massive sulfide deposits in Arizona could indicate that igneous sulfur was in much greater supply than seawater sulfur, or that recharge of the hydrothermal system was from a widespread, but stagnant and stratified layer of seawater that was isolated from more normal, sulfate-rich seawater (Eastoe and others, 1987).

Gold-Silver Zonation

The most obvious contrast in content of precious metals in the deposit, as previously noted, is from unoxidized to oxidized ore: in oxidized ore, gold and silver grades are almost an order of magnitude higher (0.03 oz Au/ton in unoxidized ore to 0.2 oz Au/ton or greater in oxidized ore, and 1.2 oz Ag/ton in unoxidized ore to 15.0 oz Ag/ton or greater in oxidized ore). However, gold and silver contents also vary considerably within the unoxidized ore where their grades are related to ore type. Smith and Sirdevan (1921, table 3) were perhaps the first to show that silica-rich ("converter flux" ore in metallurgical terminology) massive sulfide ore contained more gold and silver than normal massive sulfide (iron) or black schist (silica) ore. Subsequently, Hansen (1930), Barker (1930), and Ralston and Hunter (1930), enlarging upon these findings, indicated that precious metal contents ranged from low in quartz porphyry and black schist ore to high in massive sulfide and siliceous massive sulfide ore. Their data suggested that the deposit was zoned and that precious metal contents were greatest at the stratigraphic top.

This variation of gold and silver within ore types is further quantified by using the data of Storms (1955) for

Table D2. Average grades of ore types, United Verde massive sulfide deposit

[Number of samples averaged, in parentheses]

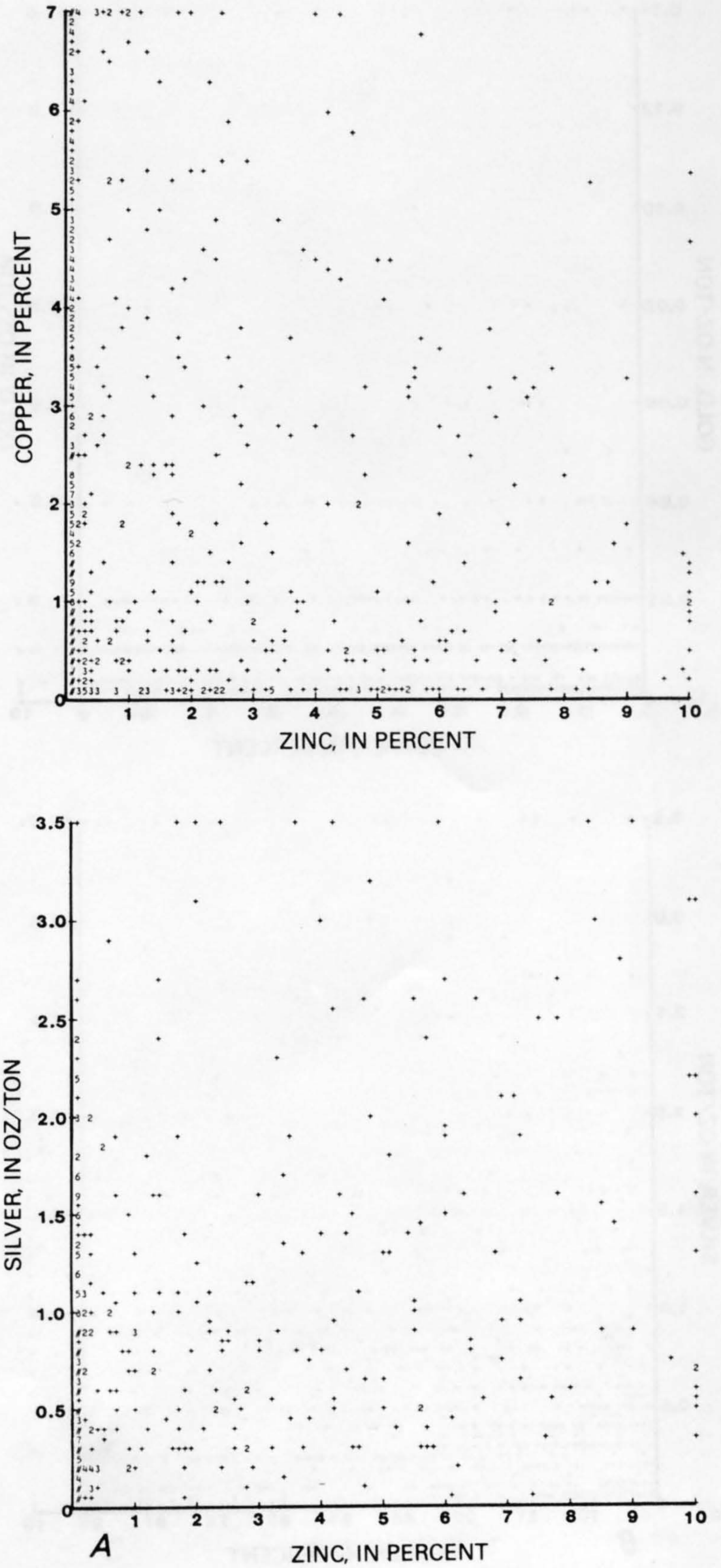
Ore type	Mine level	Copper (percent)	Zinc (percent)	Gold (oz/ton)	Silver (oz/ton)
United Verde ore body:					
Massive sulfide---	700	$1.58^{(44)}$	$10.79^{(15)}$	$0.053^{(14)}$	$3.42^{(14)}$
Chert, siliceous massive sulfide--	700	$3.45^{(16)}$			
Black schist------	700	$2.58^{(12)}$		$0.005^{(34)}$	$0.75^{(34)}$
Massive sulfide---	1200	$0.55^{(88)}$	$3.41^{(88)}$		
Black schist------	1200	$1.02^{(17)}$	$3.21^{(17)}$		
Massive sulfide---	3000	$1.80^{(109)}$	$4.90^{(98)}$	$0.020^{(43)}$	$1.56^{(31)}$
Black schist------	3000	$3.38^{(109)}$	$1.53^{(7)}$	$0.006^{(88)}$	$0.91^{(78)}$
Chert-------------	4500	$3.70^{(4)}$	$2.22^{(4)}$	$0.116^{(4)}$	$4.00^{(4)}$
Siliceous massive sulfide--	4500	$3.89^{(17)}$	$10.98^{(14)}$	$0.109^{(17)}$	$3.70^{(17)}$
Massive sulfide---	4500	$2.25^{(62)}$	$9.91^{(55)}$	$0.068^{(60)}$	$2.22^{(56)}$
Black schist------	4500	$1.35^{(21)}$		$0.002^{(9)}$	$0.71^{(9)}$
Haynes ore body:					
Massive sulfide---	3000	$0.49^{(37)}$	$4.29^{(28)}$	$0.050^{(36)}$	$0.50^{(36)}$

various levels within the United Verde deposit. Massive sulfide ore on the 700 level averages 10 times as much gold and 4–5 times as much silver as black schist ore on the same level (table D2). Massive sulfide ore on the 3000 level averages three-four times as much gold and two times as much silver as black schist ore on the same level. Grades range from 0.002 oz Au/ton and 0.71 oz Ag/ton in black schist ore, to 0.116 oz Au/ton and 4.0 oz Ag/ton in chert ore on the 4500 level. Clearly the concentration of precious metals is highest at the stratigraphic top of the deposit and gold is more enriched than silver near the top.

Correlations between precious and base metals in the deposit are not obvious if distinctions are not made among ore types (fig. D9*A*–*C*). Copper, zinc, gold, and silver analyses for a suite of samples on the 2400 level show no high positive or negative correlations among the four variables (fig. D9*A*–*C*). An important feature to note from figure D9 is that the gold and silver grades, although not positively correlated with either copper or zinc content, are just as high in zinc-rich ore (fig. D9*A*, *C*) as in copper-rich ore (fig. D9*B*).

If the data of Storms (1955) are grouped into the various ore types and plotted, correlations are noted (fig. D10, table D3). The Ag:Au ratio and precious metal grades vary with location in the deposit (fig. D10*A*). In the black schist ore the Ag:Au ratio is highest (average 170–400) and gold content lowest (about 0.005 oz Au/ton). In massive sulfide ore the Ag:Au ratio decreases to 30–100 (average for unoxidized ore about 55) and the grade increases to about 0.04 oz Au/ton. Chert ore has the lowest Ag:Au ratio (30) and the highest gold grade (0.10 oz Au/ton), and is similar in grade, although somewhat lower, to ore from the "gold stope" of the United Verde Extension mine (Anderson and Creasey, 1958; Arizona Bureau of Geology and Mineral Technology, unpub. production data, 1984; White, 1986a, 1986b). Positive correlations of gold with zinc and gold with combined zinc and copper (fig. D10*B*, *C*; table D3) are noted for massive sulfide ore. The best correlation between precious and base metals in massive and siliceous massive sulfide ore is between gold and

Figure D9 (facing and following pages). Element-element plots for the 2400 level of the United Verde massive sulfide deposit. Data from unpublished assay results made available by Phelps Dodge Corporation. Individual ore types are not plotted separately. +, one analysis; numbers 2–9, two through nine analyses plot at one point; #, more than nine analyses plot at one point. *A*, copper versus zinc (top); silver versus zinc (bottom).


COPPER, IN PERCENT
0
1
2
3
4
5
6
7
ZINC, IN PERCENT
1
2
3
4
5
6
7
8
9
10
SILVER, IN OZ/TON
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
ZINC, IN PERCENT
1
2
3
4
5
6
7
8
9
10
A

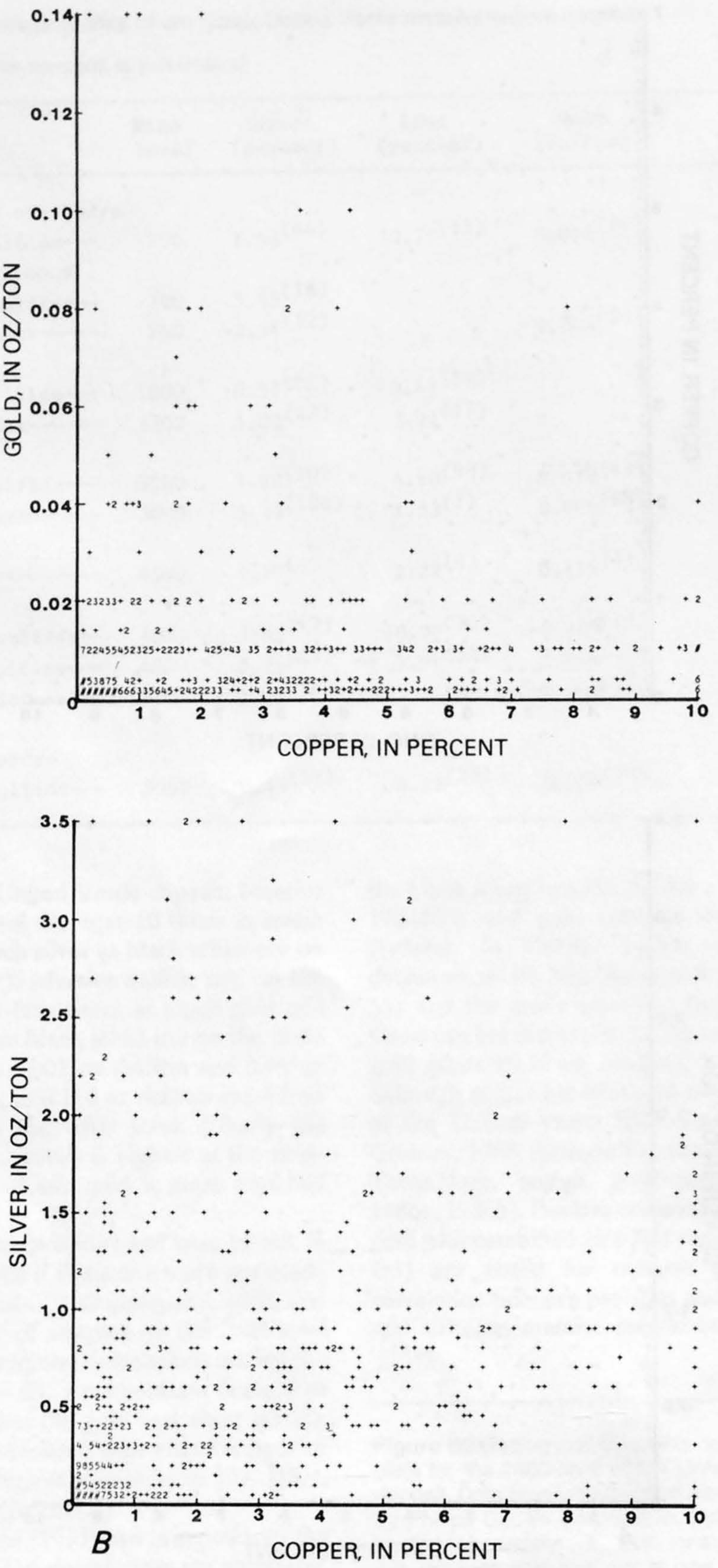


Figure D9—Continued. Element-element plots for the 2400 level of the United Verde massive sulfide deposit. *B*, gold versus copper (top); silver versus copper (bottom).

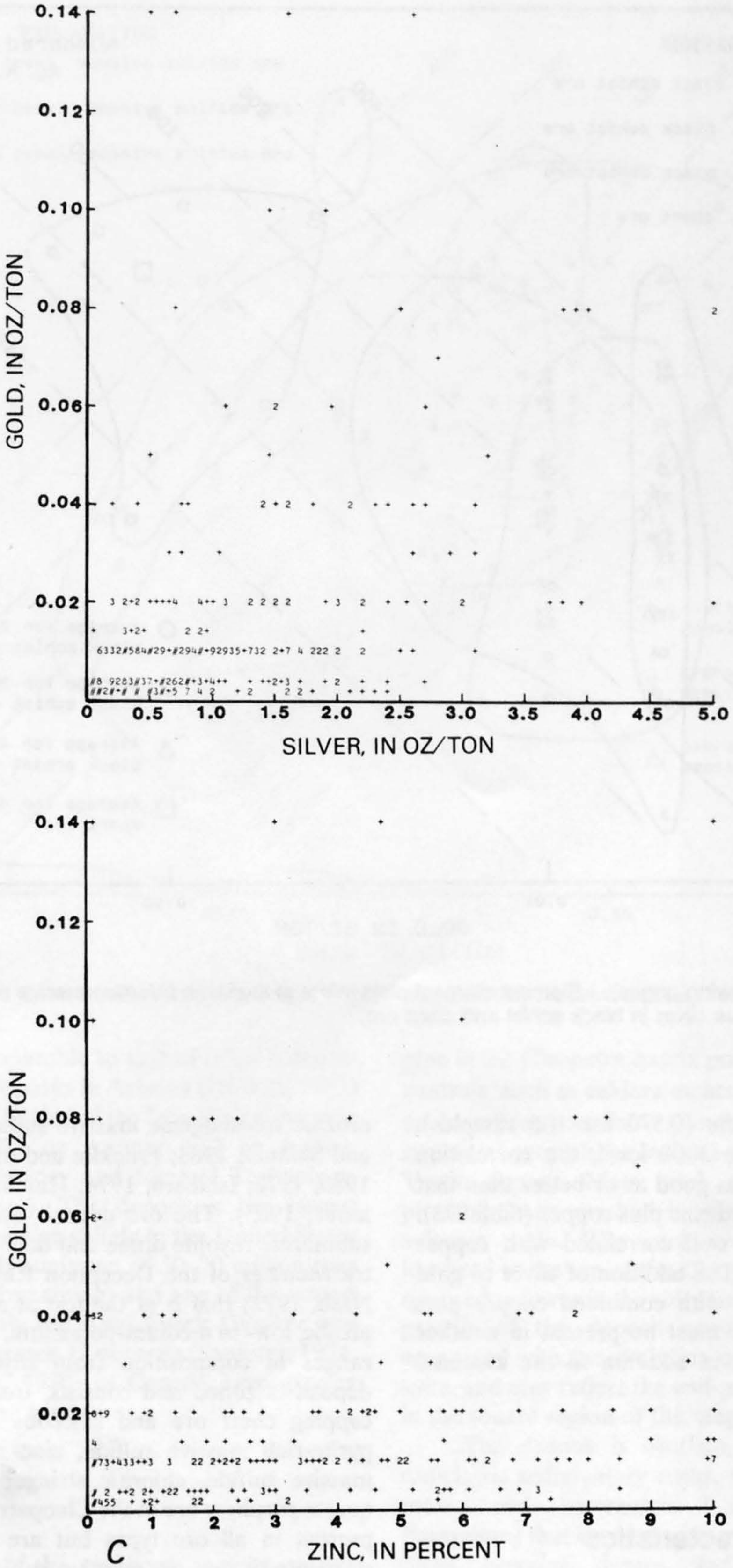


Figure D9—Continued. Element-element plots for the 2400 level of the United Verde massive sulfide deposit. *C*, gold versus silver (top); gold versus zinc (bottom).

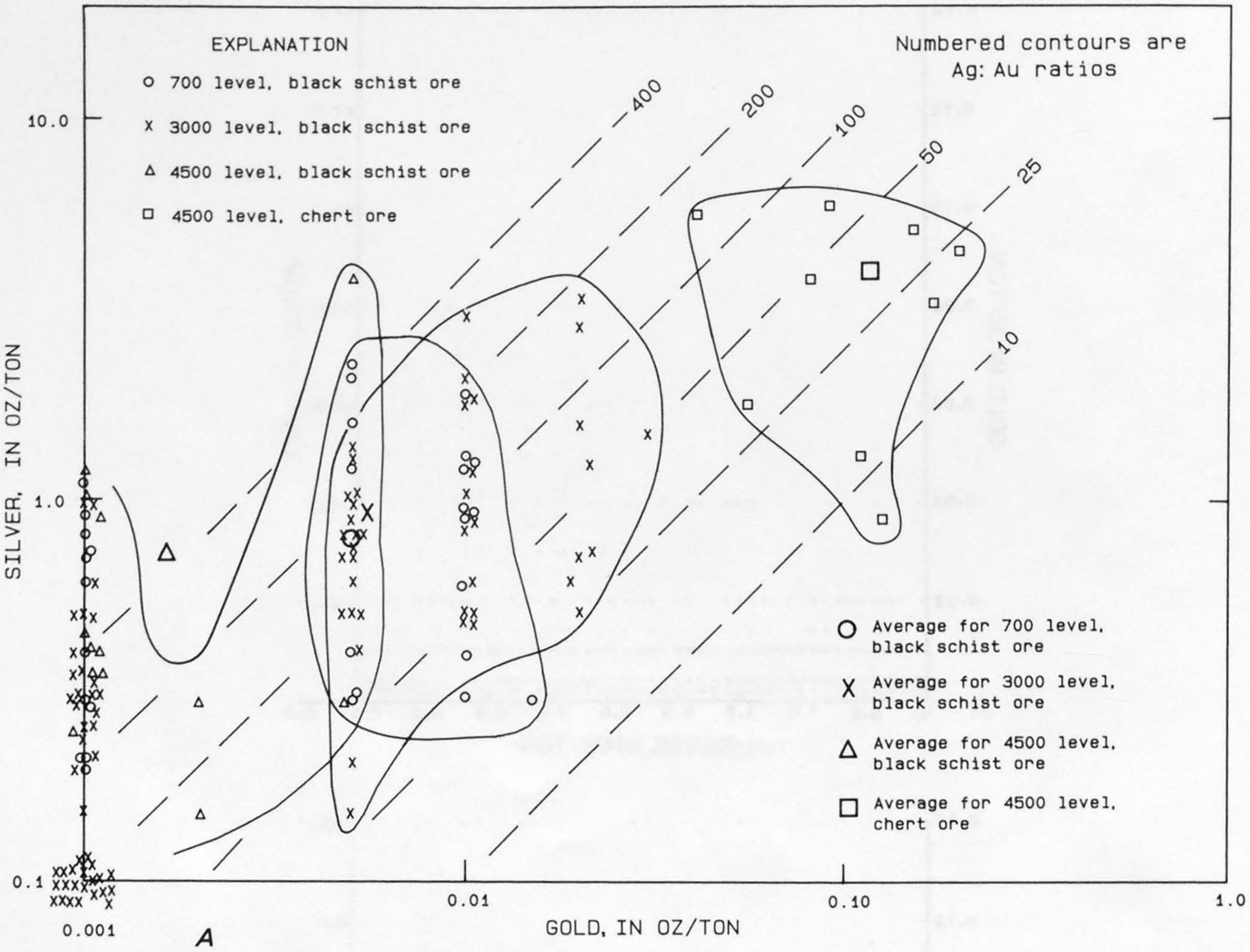


Figure D10 (above and following pages). Element-element plots in ore of the United Verde massive sulfide deposit. Data from Storms (1955). *A*, gold versus silver in black schist and chert ore.

combined copper plus zinc (0.570 for 106 samples). Except for data from the 3000 level, the correlation between zinc and gold is as good as or better than that between gold and combined zinc plus copper (table D3). Gold distribution is not well correlated with copper except on the 3000 level. The addition of silver to gold decreases the correlation with combined copper plus zinc, indicating that silver must be present in another mineral, probably galena, in addition to the assumed electrum.

CONCLUSIONS

Distinguishing Characteristics

The deposit at the United Verde mine in many respects is typical of Archean, Proterozoic, and Phanerozoic volcanogenic massive sulfide deposits (Ohmoto and Skinner, 1983; Franklin and others, 1981; Sangster, 1980, 1972; Ishihara, 1974; Hutchinson, 1973; and Gilmour, 1965). The ore deposit occurs at the top of a submarine rhyolite dome and flow breccia unit (Cleopatra Member of the Deception Rhyolite; Anderson and Nash, 1972) that is at the top of a predominantly calc-alkalic, low- to medium-potassium, iron-rich suite, which ranges in composition from rhyolite to basalt. The deposit is zoned and consists, from top to bottom, of capping chert ore and siliceous massive sulfide ore, pyrite-rich massive sulfide, zinc- and copper-zinc-rich massive sulfide, chloritic stringer ore and chloritized quartz porphyry ore in the Cleopatra. Gold and silver are present in all ore types but are concentrated at the stratigraphic top, in massive sulfide, siliceous massive sulfide (both zinc- and copper-rich), and chert ore. The grade of precious metals in the deposit (0.041 oz Au/ton;

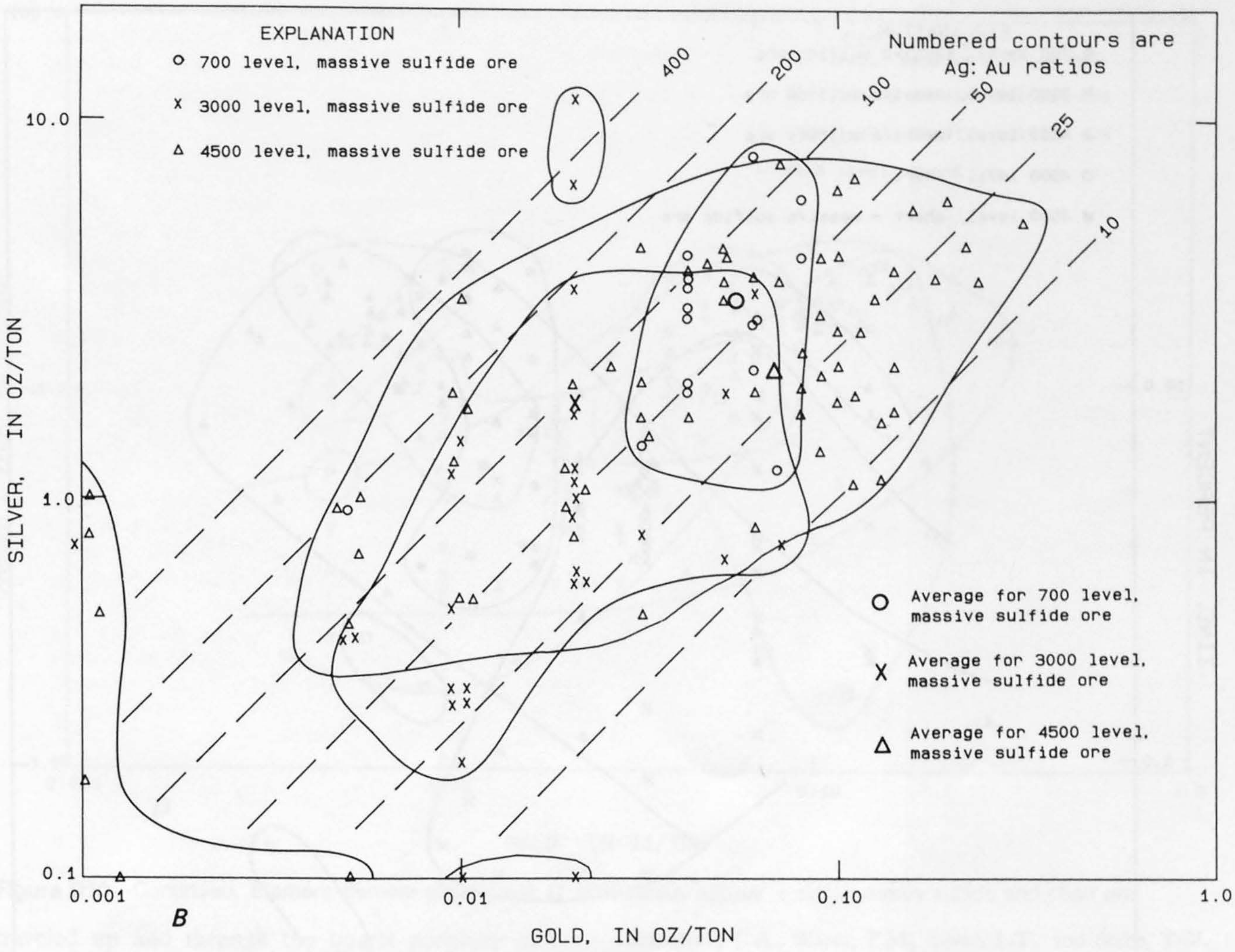


Figure D10—Continued. Element-element plots in ore. *B*, gold versus silver, massive sulfide ore.

1.49 oz Ag/ton) is comparable to that of other volcanogenic massive sulfide deposits in Arizona (DeWitt, 1983) and was exceeded only by that of the Iron King mine near Humboldt, Ariz. (0.073 oz Au/ton; 2.67 oz Ag/ton; Arizona Bureau of Geology and Mineral Technology, unpub. production data). The deposit is the largest known volcanogenic massive sulfide in the United States (33 million tons mined; minimum of 50–70 million tons of low-grade material remaining) and one of the largest in North America. Only the Kidd Creek (Walker and others, 1975) and Brunswick 12 deposits (Sangster, 1984; McAllister and others, 1980) in Canada have greater reserves plus production tonnages.

Ore Controls

The localization of the stratiform massive sulfide body was controlled by a hydrothermal conduit now represented by the chlorite schist and chloritic alteration pipe in the Cleopatra quartz porphyry. Paleotopographic controls, such as caldera moats, flanks of domes, and so on, have been postulated (Lindberg, 1986a, 1986b) as the structural controls for hydrothermal fluids at the United Verde deposit. Many such structural features have probably been masked by deformation of the metavolcanic rocks. Why such a large sulfide body was localized at the top of the Cleopatra quartz porphyry, as opposed to lower in the volcanic pile, is unknown, but the genesis of the deposit must have been intimately associated with the evolution of the submarine volcanic suite, and may reflect the end-products of differentiation in the source region of the magmas.

The deposit is overlain by a sequence of volcaniclastic sedimentary rocks, tuffs, cherty sedimentary rocks, and jasper-rich beds (Grapevine Gulch Formation) that is compositionally unlike the underlying flows, breccias, domes, and intrusives. Therefore, formation of the massive sulfide deposit appears to have marked the end of the period of submarine calc-alkalic

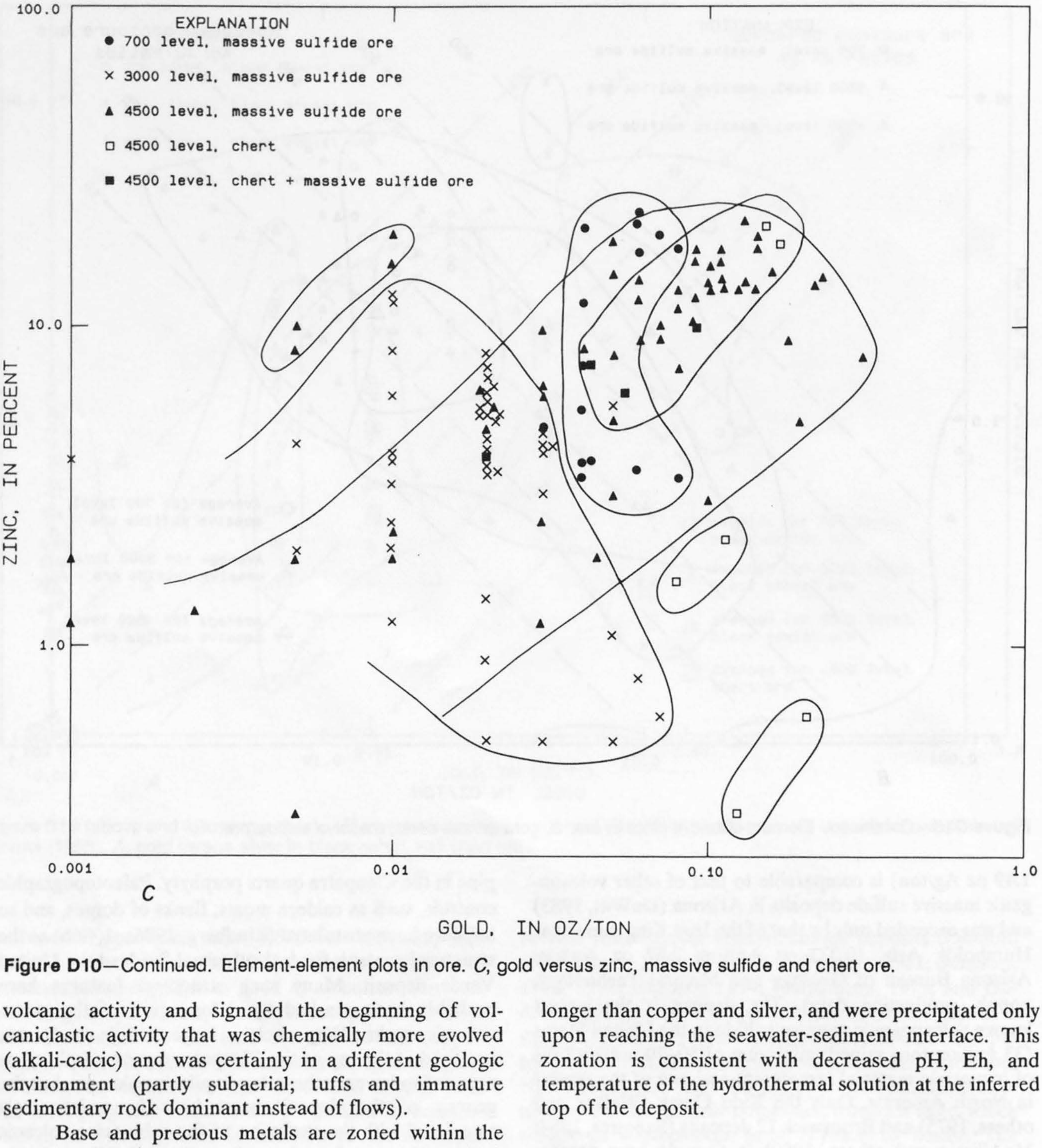


Figure D10—Continued. Element-element plots in ore. *C*, gold versus zinc, massive sulfide and chert ore.

volcanic activity and signaled the beginning of volcaniclastic activity that was chemically more evolved (alkali-calcic) and was certainly in a different geologic environment (partly subaerial; tuffs and immature sedimentary rock dominant instead of flows).

Base and precious metals are zoned within the deposit; the alteration pipe contains average to high copper but very little zinc, gold, or silver. The massive sulfide body has average to high copper, zinc, gold, and silver. The capping siliceous massive sulfide horizon and chert layers contain base and precious metals in concentrations similar to those of the highest parts of the massive sulfide ores. If all the metals were transported through the alteration pipe to the paleosurface by hydrothermal solutions, zinc and gold were retained in solution longer than copper and silver, and were precipitated only upon reaching the seawater-sediment interface. This zonation is consistent with decreased pH, Eh, and temperature of the hydrothermal solution at the inferred top of the deposit.

Origin

The United Verde deposit was formed in a Proterozoic submarine environment during deposition of rhyolite flows, tuffs, and pyroclastic material. The massive sulfide body and underlying chloritic alteration pipe are the end products of hydrothermal solutions enriched in copper, zinc, lead, gold, and silver that

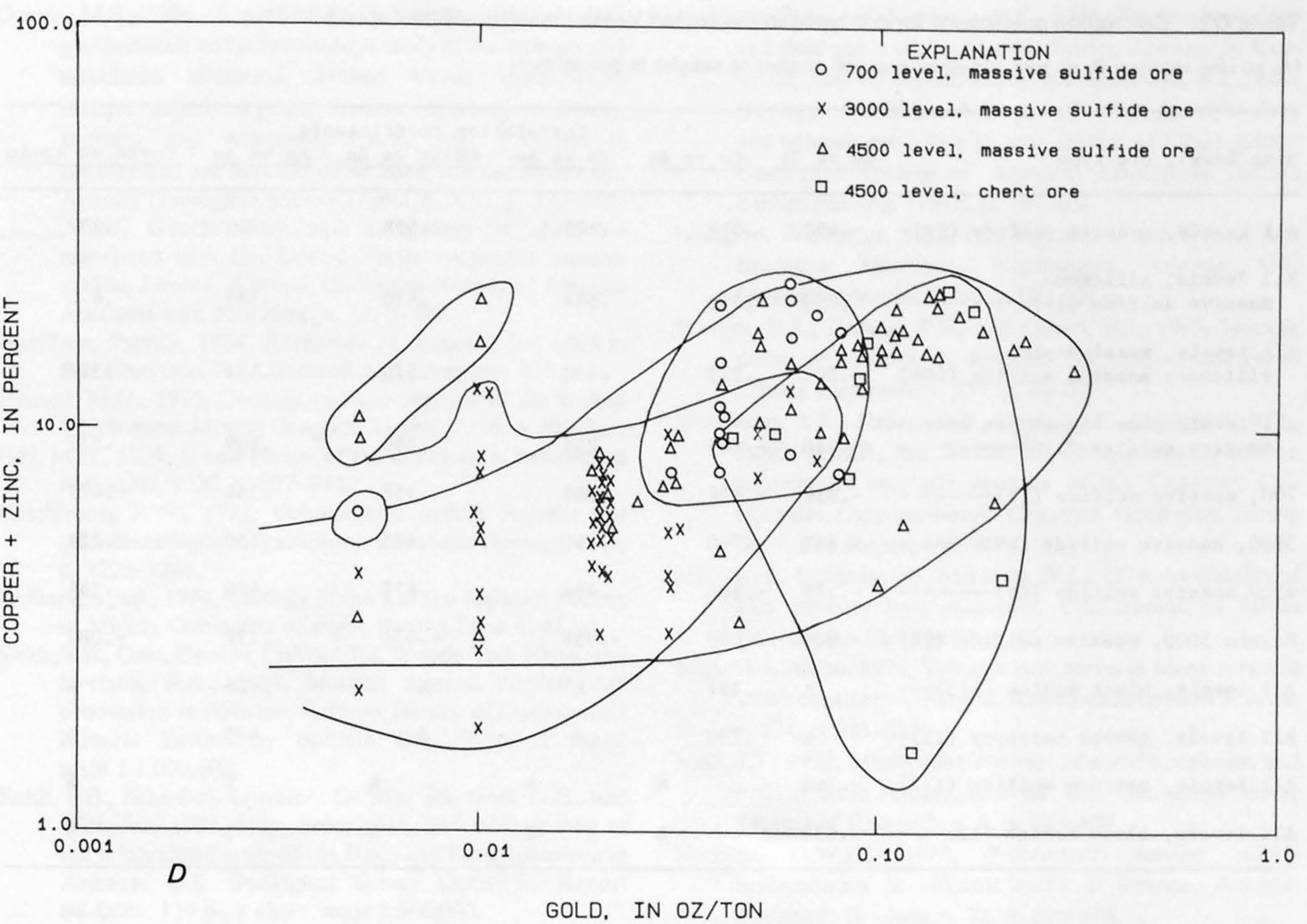


Figure D10—Continued. Element-element plots in ore. *D*, gold versus copper + zinc, massive sulfide and chert ore.

traveled up and through the quartz porphyry of the Cleopatra Member and ultimately precipitated their sulfide minerals near or at the seawater interface. Chemical studies have not been completed that would indicate the ultimate source of metals in the deposit, whether that source be the underlying volcanic pile (leaching and redistribution of metals) or the magma reservoir of the Cleopatra quartz porphyry (primary enrichment of metals in the magma).

Manuscript received by scientific editors May 1985

REFERENCES CITED

Alenius, E.M.J., 1930, Methods and costs of stripping and mining at the United Verde open-pit mine, Jerome, Arizona: U.S. Bureau of Mines Information Circular 6248, 33 p.

_____ 1968, A brief history of the United Verde open pit, Jerome, Arizona: Arizona Bureau of Mines Bulletin 178, 34 p.

Anderson, C.A., and Blacet, P.M., 1972, Precambrian geology of the northern Bradshaw Mountains, Yavapai County, Arizona: U.S. Geological Survey Bulletin 1336, 82 p.

Anderson, C.A., Blacet, P.M., Silver, L.T., and Stern, T.W., 1971, Revision of the Precambrian stratigraphy in the Prescott-Jerome area, Yavapai County, Arizona: U.S. Geological Survey Bulletin 1324–C, p. C1–C16.

Anderson, C.A., and Creasey, S.C., 1958, Geology and ore deposits of the Jerome area, Yavapai County, Arizona: U.S. Geological Survey Professional Paper 308, 185 p.

_____ 1967, Geologic map of the Mingus Mountain quadrangle, Yavapai County, Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ–715, scale 1:62,500.

Anderson, C.A., and Nash, J.T., 1972, Geology of the massive sulfide deposits at Jerome, Arizona—A reinterpretation: Economic Geology, v. 67, p. 845–863.

Anderson, C.A., Scholz, E.A., and Strobell, J.D., Jr., 1955, Geology and ore deposits of the Bagdad area, Yavapai County, Arizona: U.S. Geological Survey Professional Paper 278, 103 p.

Anderson, C.A., and Silver, L.T., 1976, Yavapai Series—A greenstone belt: Arizona Geological Society Digest, v. 10, p. 13–26.

Anderson, Phillip, 1978, The island arc nature of Precambrian volcanic belts in Arizona: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 156.

Table D3. Correlation coefficients for ore types in the United Verde massive sulfide deposit

[A, no zinc analyses; B, no gold and silver analyses; number of samples in parentheses]

	Correlation coefficients					
Mine level, ore type	Cu vs Zn	Cu vs Au	Zn vs Au	Cu+Zn vs Au	Ag vs Au	Cu+Zn vs Ag+Au
All levels, massive sulfide (92)-	-.400	.024	.475	.528	.385	.232
All levels, siliceous massive sulfide (14)-----------	.090	.398	.514	.610	.335	.470
All levels, massive plus siliceous massive sulfide (106)	-.302	.173	.480	.570	.434	.316
All levels plus Haynes ore body, massive sulfide (120)----------	-.260	-.007	.256	.260	.209	.337
700, massive sulfide (15)--------	-.938	-.428	.388	.357	.381	-.471
3000, massive sulfide (29)-------	-.643	.740	-.480	.475	.150	.221
4500 massive sulfide (48)--------	-.279	-.104	.484	.477	.486	.264
Haynes 3000, massive sulfide (28)	-.040	.060	-.086	-.071	.127	-.081
All levels, black schist (115)---	A	.291	A	A	.426	A
All levels, quartz porphyry (15)-	A	.293	A	A	.495	A
All levels, massive sulfide (137)	-.168	B	B	B	B	B
All levels, black schist (22)----	-.035	B	B	B	B	B

Anderson, Phillip, and Guilbert, J.M., 1979, The Precambrian massive sulfide deposits of Arizona—A distinct metallogenic epoch and province: Nevada Bureau of Mines and Geology Report 33, p. 39–48.

Baker, Arthur III, and Clayton, R.L., 1968, Massive sulfide deposits of the Bagdad district, Yavapai County, Arizona, *in* Ridge, J.D., ed., Ore deposits of the United States, 1933–1967 [Graton-Sales Volume]: American Institute of Mining and Metallurgical Engineers, New York, p. 1311–1327.

Barker, L.M., 1930, Concentrating plant of the United Verde Copper Company: Mining Congress Journal, v. 16, p. 363–368.

De la Roche, E., Leterrier, J., Grandclaude, P., and Marchal, M., 1980, A classification of volcanic and plutonic rocks using R_1R_2-diagram and major-element analyses—Its relationships with current nomenclature: Chemical Geology, v. 29, p. 183–210.

DeWitt, Ed, 1979, New data concerning Proterozoic volcanic stratigraphy and structure in central Arionza and its importance in massive sulfide exploration: Economic Geology, v. 74, p. 1371–1382.

_____ 1983, Precious metal content of Proterozoic massive sulfide deposits in Arizona: Geological Society of America Abstracts with Programs, v. 15, p. 298.

DeWitt, Ed, and Waegli, Jerome, 1986, Gold in the United Verde massive sulfide deposit, Jerome, Arizona: U.S. Geological Survey Open-File Report 86–0585, 41 p.

Doe, B.R., and Stacey, J.S., 1974, The application of lead isotopes to the problems of ore genesis and ore prospect evaluation—A review: Economic Geology, v. 69, p. 757–776.

Donnelly, M.E., and Hahn, G.A., 1981, A review of the Precambrian volcanogenic massive sulfide deposits in central Arizona and the relationship to their depositional environment, *in* Dickinson, W.R., and Payne, W.D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. XIV, p. 11–21.

Eastoe, C.J., Gustin, M.S., Hurlbut, D.F., and Orr, Richard, 1987, Sulfur isotopes in Proterozoic syngenetic sulfide deposits, Arizona; implications for geochemistry of seawater-rock interaction: Geological Society of America Abstracts with Programs, v. 19, p. 650.

Franklin, J.M., Lydon, J.W., and Sangster, D.F., 1981, Volcanic-associated massive sulfide deposits: Economic Geology, 75th Anniversary Volume, p. 485–627.

Gilmour, Paul, 1965, The origin of the massive sulphide mineralization in the Noranda district, northwestern Quebec: Geological Association of Canada Proceedings, v. 16, p. 63–81.

Gilmour, Paul, and Still, A.R., 1968, The geology of the Iron King mine, *in* Ridge, J.D., ed., Ore deposits of the United States, 1933–1967 [Graton-Sales Volume]: American Institute of Mining and Metallurgical Engineers, New York, p. 1238–1257.

Gustin, M.S., 1986, A preliminary report on a petrological, geochemical, and stable-isotope study of the orebody and associated alteration, United Verde volcanogenic massive sulfide deposit, Jerome, Arizona, *in* Beatty, Barbara, and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. XVI, p. 339–342.

______ 1987, Geochemistry and mineralogy of alteration associated with the United Verde syngenetic massive sulfide, Jerome, Arizona: Geological Society of America Abstracts with Programs, v. 19, p. 688.

Hamilton, Patrick, 1884, Resources of Arizona, 3rd edition: San Francisco, A.L. Bancroft and Company, 414 p.

Hansen, M.G., 1930, Geology and ore deposits of the United Verde mine: Mining Congress Journal, v. 16, p. 306–311.

Hey, M.H., 1954, A new review of the chlorites: Mineralogical Magazine, v. 30, p. 277–292.

Hutchinson, R.W., 1973, Volcanogenic sulfide deposits and their metallogenic significance: Economic Geology, v. 68, p. 1223–1246.

Ishihara, S., ed., 1974, Geology of the Kuroko deposits: Society of Mining Geologists of Japan Special Issue 6, 437 p.

Keith, S.B., Gest, Donald, DeWitt, Ed, Woode-Toll, Netta, and Everson, B.A., 1984, Metallic mineral districts and production in Arizona: Arizona Bureau of Geology and Mineral Technology Bulletin 194, 58 p., 1 sheet, scale 1:1,000,000.

Keith, S.B., Schnabel, Lorraine, DeWitt, Ed, Gest, D.E., and Wilt, Jan, 1983, Map, description, and bibliography of the mineralized areas of the Basin and Range province in Arizona: U.S. Geological Survey Open-File Report 84–0086, 129 p., 1 sheet, scale 1:500,000.

Krieger, M.H., 1965, Geology of the Prescott and Paulden quadrangles, Arizona: U.S. Geological Survey Professional Paper 467, 127 p.

Krieger, Philip, 1932, Geology of the zinc-lead deposit at Pecos, New Mexico: Economic Geology, v. 27, Pt. I, p. 344–364; Pt. II, p. 450–470.

Larson, P.B., 1984, Geochemistry of the alteration pipe at the Bruce Cu-Zn volcanogenic massive sulfide deposit, Arizona: Economic Geology, v. 79, p. 1880–1896.

______ 1987, Geology and oxygen isotope geochemistry of the Bruce volcanogenic massive sulfide deposit, Bagdad, Arizona: Geological Society of America Abstracts with Programs, v. 19, p. 740.

Lindberg, P.A., 1986a, Genesis of Proterozoic massive sulfide deposits and structural geology of the Jerome district, Arizona: Geological Society of America Abstracts with Programs, v. 18, p. 390.

______ 1986b, A brief geologic history and field guide to the Jerome district, Arizona, *in* Nations, J.D., Conway, C.M., and Swann, G.A., eds., Geology of central and northern Arizona: Geological Society of America Rocky Mountain Section Guidebook, p. 127–139.

Lindberg, P.A., and Gustin, M.S., 1987, Field-trip guide to the geology, structure, and alteration of the Jerome, Arizona ore deposits, *in* Davis, G.H., and VandenDolder, E.M., eds., Geologic diversity of Arizona and its margins; excursions to choice areas: Arizona Bureau of Geology and Mineral Technology Special Paper 5, p. 176–181.

Lindberg, P.A., and Jacobson, H.S., 1974, Economic geology and field guide of the Jerome district, Arizona, *in* Karlstrom, T.N.V., Swann, G.A., and Eastwood, R.L., eds., Geology of northern Arizona with notes on archeology and paleoclimate; Part II, area studies and field guides: Geological Society of America, Cordilleran section annual meeting, Trip 8, p. 794–804.

Lindgren, Waldemar, 1926, Ore deposits of the Jerome and Bradshaw Mountains quadrangles, Arizona: U.S. Geological Survey Bulletin 782, 192 p.

Mauger, R.L., Damon, P.E., and Giletti, B.J., 1965, Isotopic dating of Arizona ore deposits: Transactions, Society of Mining Engineers, v. 232, p. 81–87.

McAllister, A.L., Strong, D.F., Davies, J.L., Lamarche, R.Y., Sangster, D.F., and Zentilli, M., 1980, Summary data on stràtabound sulphide deposits in the Canadian Caledonides (Appalachians): Canadian Geological Survey Open File Report 677, 40 p.

McIlroy, P., Coffman, J.S., and Rice, W.L., 1974, Availability of U.S. primary lead resources: U.S. Bureau of Mines Information Circular 8646, 46 p.

Miyashiro, Akiho, 1974, Volcanic rock series in island arcs and active continental margins: American Journal of Science, v. 274, p. 321–355.

Nash, J.T., 1973, Microprobe analyses of sericite, chlorite, and epidote from Jerome, Arizona: U.S. Geological Survey Journal of Research, v. 1, p. 673–678.

Norman, G.W.H., 1977, Proterozoic massive sulfide replacements in volcanic rocks at Jerome, Arizona: Economic Geology, v. 72, p. 642–656.

Ohmoto, Hiroshi, and Skinner, B.J., eds., 1983, The Kuroko and related volcanogenic massive sulfide deposits: Economic Geology Monograph 5, 604 p.

Peacock, M.A., 1931, Classification of igneous rock series: Journal of Geology, v. 39, p. 54–67.

Peccerillo, A., and Taylor, S.R., 1976, Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey: Contributions to Mineralogy and Petrology, v. 58, p. 63–81.

Provot, F.A., 1916, Jerome mining district geology: Engineering and Mining Journal, v. 102, p. 1028–1031.

Ralston, O.C., 1930, Possibilities of zinc production in Arizona: Mining Journal, v. 14, p. 11.

Ralston, O.C., and Hunter, W.C., 1930, Activation of sphalerite for flotation: American Institute of Mining and Metallurgical Engineers Transactions, v. 87, p. 411–416.

Reber, L.E., Jr., 1922, Geology and ore deposits of Jerome district: American Institute of Mining and Metallurgical Engineers Transactions, v. 66, p. 3–26.

______ 1938, Jerome district, *in* Some Arizona ore deposits: Arizona Bureau of Mines Bulletin 145, p. 41–65.

Rickard, T.A., 1918, The story of the U.V.X. bonanza: Mining and Scientific Press, v. 116, p. 9–17, 47–52.

Riesmeyer, W.D., 1978, Precambrian geology and ore deposits of the Pecos mining district, San Miguel and Santa Fe Counties, New Mexico: Albuquerque, N. Mex., University of New Mexico M.S. thesis, 215 p.

Robertson, J.M., and Moench, R.H., 1979, The Pecos greenstone belt—A Proterozoic volcano-sedimentary sequence in the southern Sangre de Cristo Mountains, New Mexico: New Mexico Geological Society Guidebook 30th field conference, Santa Fe, p. 165–173.

Saggerson, E.P., and Turner, L.M., 1982, General comments on the identification of chlorites in thin sections: Mineralogical Magazine, v. 46, p. 469–473.

Sangster, D.F., 1972, Precambrian massive sulphide deposits in Canada—A review: Canadian Geological Survey Paper 72–22, 44 p.

_____ 1980, Distribution and origin of Precambrian massive sulphide deposits of North America: Geological Association of Canada Special Paper 20, p. 723–740.

_____ 1984, Grade-tonnage summaries of massive sulfide deposits relative to paleotectonic settings in the Appalachian-Caledonian orogen: Economic Geology, v. 79, p. 1479–1482.

Shand, S.J., 1927, The eruptive rocks: New York, John Wiley, 488 p.

Slavin, Morris, 1930, Ore-dressing microscopy at United Verde: Mining Congress Journal, v. 16, p. 386–387.

Smith, H.D., and Sirdevan, W.H., 1921, Mining methods and costs at the United Verde mine: American Institute of Mining and Metallurgical Engineers Transactions, v. 65, p. 127–181.

Stacey, J.S., Doe, B.R., Silver, L.T., and Zartman, R.E., 1976, Plumbotectonics IIA, Precambrian massive sulfide deposits: U.S. Geological Survey Open-File Report 76–476, 26 p.

Stacey, J.S., and Kramers, John, 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Sciences Letters, v. 26, p. 207–221.

Steiger, R.H., and Jaeger, Emile, 1977, Subcommission on geochronology; convention and use of decay constants in geo- and cosmochronology: Earth and Planetary Sciences Letters, v. 36, p. 359–362.

Stensrud, H.L., and More, Syver, 1980, Precambrian geology and massive sulfide environments of the west-central Hualapai Mountains, Mohave County, Arizona—A preliminary report: Arizona Geological Society Digest, v. XII, p. 155–166.

Storms, W.R., 1955, Selenium samples from the United Verde Branch, Phelps Dodge Corporation, Jerome, Arizona: U.S. Bureau of Mines Open-File report, 55 p.

Vance, R.K., and Condie, K.C., 1986, Geochemistry and tectonic setting of the early Proterozoic Ash Creek Group, Jerome, Arizona: Geological Society of America Abstracts with Programs, v. 18, p. 419.

_____ 1987, Geochemistry of footwall alteration associated with the Early Proterozoic United Verde massive sulfide deposit, Jerome, Arizona: Economic Geology, v. 82, p. 571–586.

Vrba, S.L., 1980, Precambrian geology of the Cleator area, Yavapai County, Arizona: Flagstaff, Ariz., Northern Arizona University M.S. thesis, 96 p.

Walker, R.R., Matulich, A., Amos, A.C., Watkins, J.J., and Mannard, G.W., 1975, The geology of the Kidd Creek mine: Economic Geology, v. 70, p. 80–89.

White, Don, 1986a, Gold distribution at the United Verde Extension, a massive base-metal sulfide deposit, Jerome, Arizona, *in* Beatty, Barbara, and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. XVI, p. 330–338.

_____ 1986b, Gold exploration at the United Verde Extension mine, Jerome, Arizona: Geological Society of America Abstracts with Programs, v. 18, p. 422.

The Alaska-Juneau and Treadwell Lode Gold Systems, Southeastern Alaska

By Thomas D. Light, David A. Brew, *and* Roger P. Ashley

Abstract

The Alaska-Juneau and Treadwell lode-gold systems (or deposits) in southeastern Alaska produced more than 6.7 million ounces of gold, about 75 percent of the total lode gold production from Alaska. Each system consists of four separate contiguous ore bodies aligned in a northwesterly direction along the regional structural trend. The composition and competence of the stratigraphic units as well as the structural setting were major factors in localizing the individual ore bodies. At the Alaska-Juneau deposit, gold, silver, and lead occur in quartz veins in hydrothermally altered amphibolite, phyllite, and schist. Albite diorite sills at the Treadwell deposit host gold-bearing calcite and quartz veins and stringers as well as disseminated gold. Both lode-gold systems were emplaced, probably between 50 and 60 million years ago, at or near the end of a major regional compressive stress event and before or during the uplift of the Coast Mountains. Fluid inclusion and isotopic compositions suggest that the ore-forming fluids were derived from the metamorphism of deeper rocks rather than from circulating meteoric waters. These physical, chemical, and temporal conditions coincide with the transition from strongly compressive subduction to transpressive collision along the western margin of North America, and indicate an environment of formation similar to that of the California Mother Lode deposits.

INTRODUCTION

The Alaska-Juneau (A-J) and Treadwell systems represent the two largest lode gold deposits in Alaska, and together produced more than 6.7 million oz of gold. These deposits are located about 6 km apart on opposite sides of Gastineau Channel near Juneau, along the western flank of the Coast Mountains in southeastern Alaska (fig. D11). The deposits lie in the western metamorphic zone of the northern Coast plutonic-metamorphic complex (Brew and Ford, 1984a).

The A-J system comprises four separate ore bodies in Silverbow Basin in upper Gold Creek: the Ebner mine on the northwest end of the system, the North and South ore bodies of the Alaska-Juneau mine, and the Perseverance mine to the southeast (fig. D12). The Treadwell system on Douglas Island includes, from northwest to southeast, the Treadwell, the 700-Foot, the Mexican, and the Ready Bullion mines, located contiguously along 1,200 m of a mineralized albite diorite sill.

HISTORY, PRODUCTION, AND RESERVES

Gold was first discovered in Gold Creek, at the present site of Juneau, Alaska, during the summer of 1880 by Richard T. Harris and Joseph Juneau. Subsequently, placer deposits in Gold Creek and other nearby streams were worked for several years. The Alaska-Juneau Gold Mining Company was organized in 1897, and it mined open pits on both the North and South ore bodies in Silverbow Basin east of Juneau. Underground operations began in 1903 and continued until 1944 (Twenhofel, 1952).

The Ebner mine was worked intermittently until 1912, when U.S. Smelting and Refining Co. acquired the property. The property was idle from 1917 to 1925, when arrangements were made with the Alaska-Juneau Gold Mining Co. to mine and mill ore from the Ebner (Twenhofel, 1952). Spencer (1906) listed total production from the Ebner mine at about 29,000 oz gold. No figures are available for production after 1905.

The Perseverance mine began production in 1895, and was worked intermittently until it was acquired by the Alaska-Gastineau Mining Co. in 1912. From 1895 to 1921, approximately 500,000 oz gold was recovered from the Perseverance mine. The property was idle from 1921 until 1933, when it was purchased by the Alaska-Juneau Gold Mining Co. and was integrated into the Alaska-Juneau mine (Twenhofel, 1952).

Total lode production from the A-J system was approximately 3.5 million oz gold, 1.9 million oz silver, and 40.2 million lb lead (Berg, 1984). In addition, more than 120,000 oz gold was recovered from placer deposits in Gold Creek and Silverbow Basin (Spencer, 1906).

The A-J deposit was mined predominantly by modified block-caving, and hand-sorting was used to eliminate much of the waste. This hand-cobbing of the sulfide-bearing quartz veins eliminated approximately 45 percent of the rock mined, and raised the tenor of the ore from 0.045 to 0.086 oz Au/ton (Wayland, 1939;

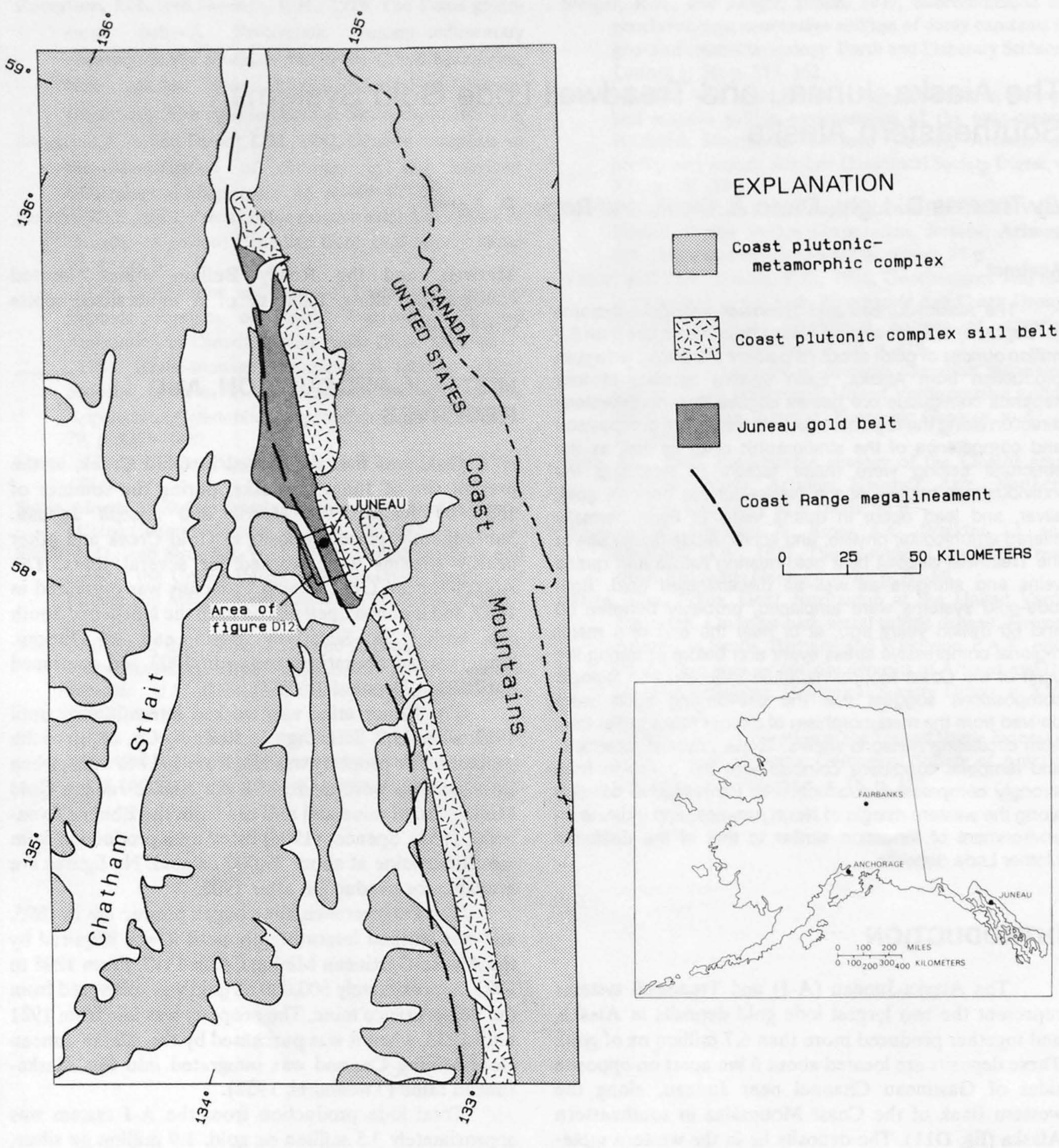


Figure D11. Index map of southeastern Alaska showing the location of Juneau.

Twenhofel, 1952). Mining at the Alaska-Juneau mine ceased in April 1944. At that time a total of 99,000,000 tons of ore had been mined from the A-J system, and the known ore reserves were about 1.4 million oz gold (Stone and Stone, 1980).

The Alaska Mill and Mining company was founded in 1882 and worked the Treadwell mine, of the Treadwell system. This property was acquired by the Alaska Treadwell Gold Mining Company in 1889. The Alaska Mexican Gold Mining Company owned the Mexican mine, and the Alaska United Gold Mining Company owned the 700-Foot and Ready Bullion mines. The companies were financially separate, but the Alaska Treadwell Gold Mining Company managed all the properties. The

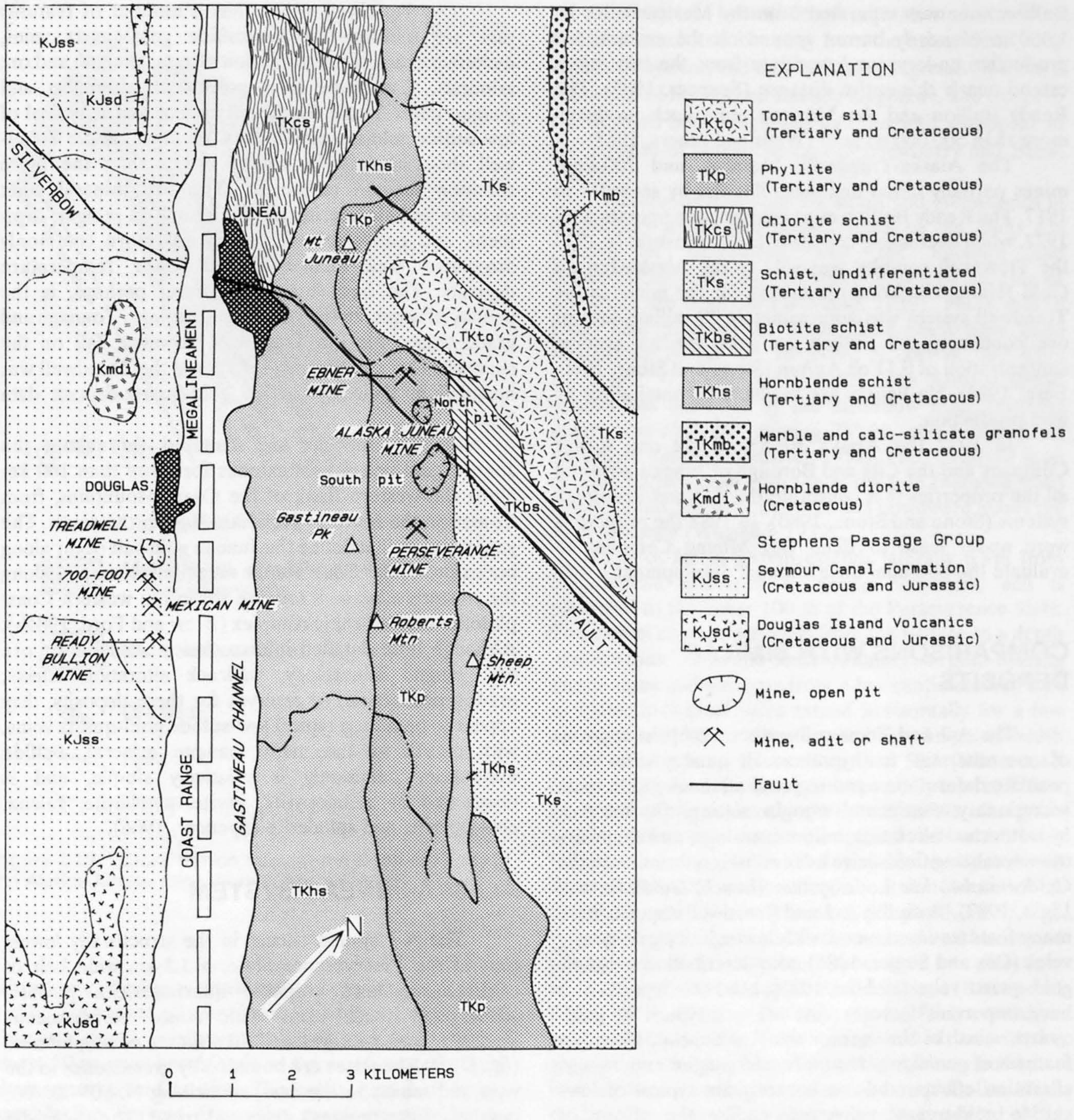


Figure D12. Generalized geologic map of Juneau area showing locations of mines in the A-J and Treadwell systems (from Brew and Ford, 1985).

Treadwell system, comprising the Treadwell, 700-Foot, Mexican, and Ready Bullion mines, was worked to a depth of about 950 m, below which the gold grade became uneconomical. In addition to the underground workings, the Treadwell mine operated an open pit until 1906. At that time the glory hole was 550 m long, 140 m wide, and 150 m deep (Stone and Stone, 1980).

More than half the ore produced from the Treadwell system came from the Alaska-Treadwell mine (Stone and Stone, 1980). The 700-Foot mine was named for the width of the strip of land which separated the Alaska-Treadwell and the Mexican mines. Approximately 247,000 oz gold was produced from the 700-Foot mine (Wells and others, 1985). The Ready

Bullion mine was separated from the Mexican mine by 1,000 m of nearly barren ground on the surface, but productive underground workings from the two mines extend nearly this entire distance (Spencer, 1905). The Ready Bullion and the Mexican mine each produced more than 500,000 oz gold (Wells and others, 1985).

The Alaska-Treadwell, Mexican, and 700-Foot mines partially caved and were flooded by seawater in 1917. The Ready Bullion mine continued to operate until 1922, when decreasing ore tenor forced closure. In 1928 the Treadwell complex was sold to the Alaska-Juneau Gold Mining Co. Total production for the mines in the Treadwell system was approximately 29 million tons of ore containing 3.2 million oz gold, for an average concentration of 0.11 oz Au/ton (Stone and Stone, 1980; Berg, 1984). No figures are available for total silver or lead production.

In 1972 the Alaska Electric Light and Power Company and the City and Borough of Juneau acquired all the properties that constitute the A-J and Treadwell systems (Stone and Stone, 1980). In 1988 the properties were under lease to Echo Bay Mining Company to evaluate the potential for additional development.

COMPARISONS WITH SIMILAR DEPOSITS

The A-J and Treadwell systems comprise a group of mesothermal to hypothermal quartz veins that postdate deformation and regional metamorphism in an accretionary continental margin setting. In the A-J, hydrothermal alteration, vein mineralogy, and chemistry of mineralizing fluids have been considered similar to the California Mother Lode system (Leach, Goldfarb, and Light, 1987). Both the A-J and Treadwell deposits have many features in common with low-sulfide, gold-quartz veins (Cox and Singer, 1986), also described as orogenic gold-quartz veins (Bohlke, 1982); but both deposits also have important features that are not typical of gold-quartz veins. In the case of the A-J deposit, all major features of geologic setting, ore and gangue mineralogy, alteration effects, and ore controls are typical of low-sulfide gold-quartz veins, except for the effects of unusual biotitic alteration, and the effects of carbonate alteration that are less prominent than in most other deposits. In addition, grade and tonnage characteristics of the A-J are strikingly different from those of more than 300 low-sulfide gold-quartz deposits used by Cox and Singer (1986) to define cumulative grade and tonnage curves for this deposit type. The gold grade of ores from the A-J is lower and the tonnage higher than in any deposit in the Cox and Singer data base, and data for the A-J were not included in their grade and tonnage curves.

The Treadwell system has a number of features that are unusual for low-sulfide gold-quartz veins, including character of alteration effects, gangue, and ore minerals. Carbonate is a prominent alteration and gangue phase in the Treadwell system and is typical of low-sulfide gold-quartz deposits. However, at the Treadwell the carbonate is calcite rather than the more common ferroan carbonate. The ore mineral suite includes arsenic-bearing minerals such as realgar, orpiment, and native arsenic, which are more commonly associated with shallower and lower temperature deposits. The most unusual feature, perhaps, is the paucity of quartz in the gangue assemblage. Tonnage and grade values for the Treadwell, however, fall on the curves of Cox and Singer (1986), and the Treadwell was included in their low-sulfide gold-quartz-deposit data base.

Smaller deposits are scattered throughout the Juneau gold belt, which extends for more than 160 km along the western flank of the Coast Mountains, from Comet on the north to Holkham Bay on the south. The gold deposits that define the Juneau gold belt occur along both sides of the Coast Range megalineament and along the western edge of a tonalite sill in the western Coast plutonic-metamorphic complex (Brew and Ford, 1984b). Although little detailed information is available on ore and gangue mineralogy, wallrock alteration effects, grades, production, or reserves for these deposits, they appear to be mostly typical low-sulfide gold-quartz veins, with quartz as the major gangue mineral. Sulfide mineralogy commonly is relatively simple, and is dominated by arsenopyrite, pyrite, pyrrhotite, galena, chalcopyrite, and sphalerite (Spencer, 1906).

ALASKA-JUNEAU SYSTEM

The A-J system occurs in the structurally lowest part of the Perseverance Slate, a 1.5-km-wide belt of carbonaceous and graphitic quartz-sericite phyllite, schist, and black slate with minor carbonaceous limestone and numerous sill-like lenses of amphibolite (fig. D13). The slates are bounded by greenstones to the west and schists to the east, all striking N. 50°–70° W., parallel to the regional structural trend. The slates dip from vertical in Sheep Creek on the south, to about 60° NE. in Silverbow Basin, and to 40° NE. farther to the northwest (Wayland, 1939). The age of the protoliths of the Perseverance Slate and adjacent metavolcanic rocks is interpreted to be Permian(?) and Late Triassic (Brew and Ford, 1977).

The amphibolite lenses within the Perseverance Slate range in size from a few centimeters wide and several meters long to more than 300 m wide and 3 km long. The amphibolites were derived from a gabbroic protolith (composed of hornblende, augite, and

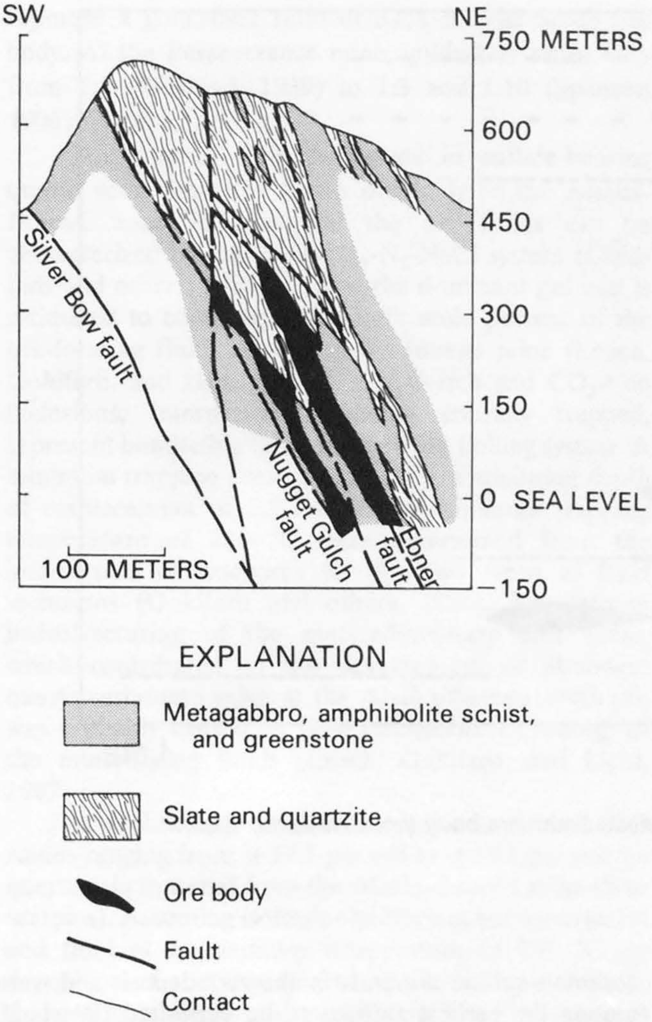


Figure D13. Cross section through the North ore body of the Alaska-Juneau mine (from Wernecke, 1932).

labradorite) during regional metamorphism (Twenhofel, 1952). Two types of amphibolite have been recognized. One is a green, relatively unaltered rock composed of about 50 percent hornblende in a groundmass of plagioclase, quartz, and zoisite. The other type is a brown amphibolite derived from the green amphibolite by hydrothermal alteration associated with the emplacement of the mineralized quartz veins. This hydrothermal alteration formed biotite, ankerite, and sericite with some chlorite and albite at the expense of hornblende and feldspar, and destroyed the schistosity of the amphibolite (Twenhofel, 1952). The brown amphibolite is composed of about 35 percent biotite, 35 percent ankerite, 20 percent feldspar (andesine to oligoclase with minor albite), and varied amounts of pyrrhotite, chlorite, and sericite. Most of the ankerite is later than and follows the quartz veins (Wayland, 1939).

Effects of hydrothermal alteration have been traced as much as 1 km away from the mineralized zone of the A-J system, and they increase progressively toward the center of the system. Initially magnetite, and closer to the deposits both magnetite and ilmenite, disappear at the expense of pyrrhotite±pyrite (Newberry and Brew, 1988).

Numerous faults cut the slates and greenstones in the vicinity of the ore bodies. Most of the faults are parallel or subparallel with the foliation and compositional layering, but splitting and converging of the faults are common (Wayland, 1939). Three sets of joints that predate the mineralized veins have been recognized: N. 30° E., 76° NW.; N. 34° W., 40° SW.; N.–S., 45° W. (Twenhofel, 1952). The Alaska-Juneau deposit has been cut by the Silverbow fault, trending nearly east-west and dipping 75° N., and hundreds of subsidiary faults (Twenhofel, 1952). The Silverbow is an oblique normal fault with the north side (hanging wall) moved about 550 m to the west and downward about the same distance (Wayland, 1939).

The A-J vein system extends laterally 6 km from Mt. Juneau southeast to Sheep Mountain, and is restricted to the lower 100 m of the Perseverence Slate. The system extends vertically from the surface to a depth of more than 700 m and contains numerous gold-bearing quartz veins and stringers from a few centimeters to 1 m in width. Individual veins extend horizontally for a few tens to several hundred meters, and have height-to-width ratios ranging from 1:1 to more than 50:1 (Barton and Light, 1987). Early barren veins reportedly tend to follow the trend of the schistosity (Wayland, 1939). The gold-bearing quartz veins have well-defined walls within both the slate and amphibolite. The veins commonly make an angle of about 20° to the schistosity, strike from north to N. 70° W., and dip nearly vertical (Wayland, 1939). The veins are boudinaged in both the vertical and horizontal planes, indicating extension in more than one direction, and in places have been sheared and rotated (Barton and Light, 1987). Because the veins have a fairly consistent gold content, the most favorable ground is that with the greatest density of veining. The gold grade may be higher in veins near interfingering slate and amphibolite. High gold concentrations do not occur in veins restricted either to the massive green amphibolite or to slate without amphibolite lenses (Twenhofel, 1952).

The veins of the A-J system are about 95 percent quartz with subsidiary ankerite, pyrrhotite, galena, sphalerite, arsenopyrite, pyrite, and gold (Twenhofel, 1952). Wayland (1939, 1960) described the paragenetic sequence of base and precious metals at the Alaska-Juneau mine (fig. D14). The gold in the A-J deposit is contained almost entirely within the quartz stringers and veins (Wayland, 1939). Gold is the last of the metals to have been deposited, and it tends to be concentrated with

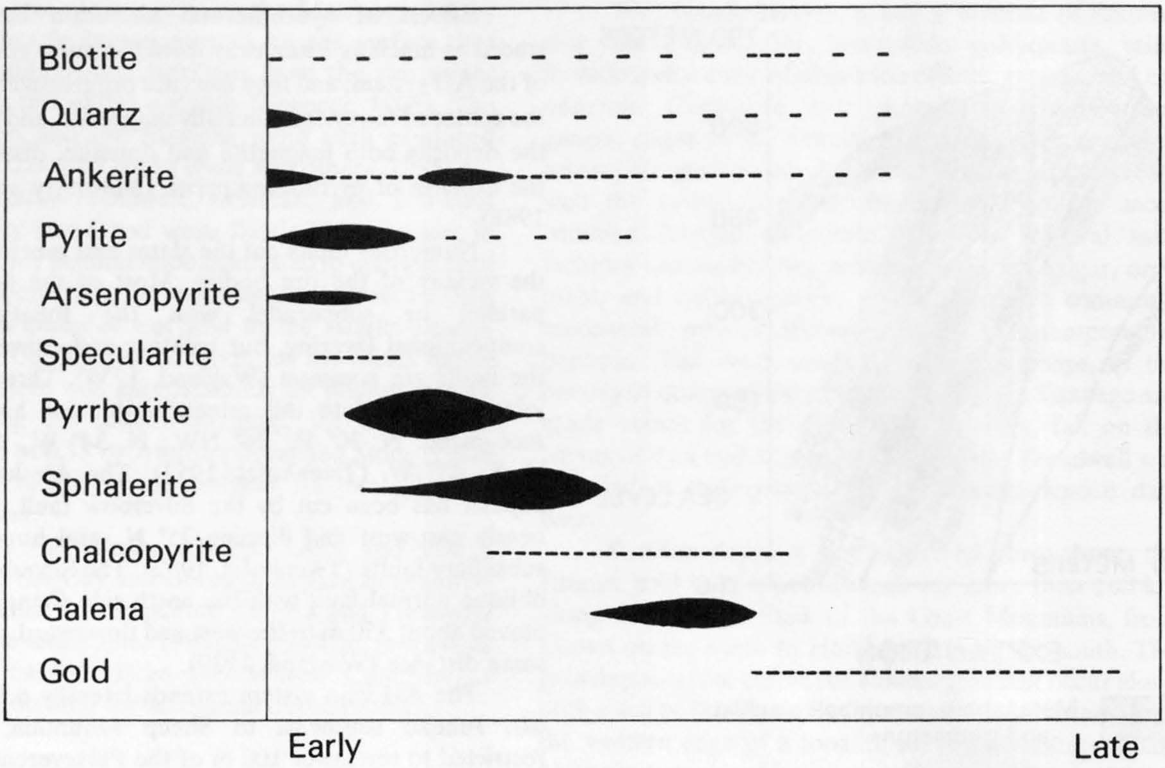


Figure D14. Paragenesis of minerals in the Alaska-Juneau South ore body (from Wayland, 1960).

sulfide minerals along the edges of the larger quartz veins, along the boundaries of sulfide minerals, and in late fractures in ankerite and quartz. Although much of the gold occurs along sulfide boundaries, approximately 90 percent is free gold and is easily released during crushing (Twenhofel, 1952). Silver occurs in recoverable quantities in the A-J deposit. Native silver is not known to occur, and it has been estimated that 23 percent of the silver occurs with gold in electrum, and the remainder is combined with galena (Twenhofel, 1952).

Pyrrhotite is by far the most common sulfide mineral, and occurs in the altered wallrocks as well as in the quartz veins (Wayland, 1939). Pyrrhotite constitutes almost 1 percent of the vein material in the Alaska-Juneau mine, but does not appear to be correlated with gold distribution (Twenhofel, 1952). The abundance of pyrrhotite in the A-J system was interpreted by Newberry and Brew (1987) as one line of evidence supporting an epigenetic rather than syngenetic mineralization. Sphalerite is abundant in the Alaska-Juneau mine; it is essentially contemporaneous with pyrrhotite and predates most of the galena. Galena also is abundant in the Alaska-Juneau mine, and is one of the last sulfides to be deposited. It normally occurs near the center of quartz stringers (Wayland, 1939). Pyrite and arsenopyrite are common sulfide minerals in the A-J deposit and were among the earliest sulfides to be deposited (Wayland, 1939). Chalcopyrite occurs in minor amounts in the A-J deposit, commonly associated with sphalerite (Twenhofel, 1952).

Ankerite, aside from quartz, is the most abundant gangue mineral, and it normally occupies the edges of veins, separating the quartz from the country rock. Ankerite formed later than all the other minerals except gold (Twenhofel, 1952). Sericite occurs both in the host rocks as a metamorphic mineral and as a late-stage hydrothermal mineral along vein edges (Twenhofel, 1952). In general, the abundance of sulfide minerals in the veins increases from the Ebner deposit, where sulfides are minor and pyrrhotite is the dominant species, to the South ore body, where sulfides are abundant and varied. Southeast of the South ore body, at the Perseverance mine, pyrrhotite is still the dominant sulfide, but sphalerite and galena are more abundant and arsenopyrite reaches its greatest abundance. The sulfide content decreases in Sheep Creek (immediately south of the Perseverance mine), where sphalerite and galena dominate. The gold:silver ratio gradually decreases to the southeast. Gold:silver ratios from the Ebner mine were 7:1 (Spencer, 1906) and 6.5:1 (Scott, 1932). Smith (1941) reported a gold:silver ratio of 5.6:1 for the South ore body. At the Perseverance mine, gold:silver ratios vary from 1:1 (Wayland, 1939) to 1:3 and 1:10 (Spencer, 1906).

Analyses of fluid inclusions in sulfide-bearing quartz veins from the South ore body of the Alaska-Juneau mine indicate that the ore fluids can be characterized by the H_2O-CO_2-N_2-NaCl system (Goldfarb and others, 1986). CO_2 is the dominant gas and is estimated to compose 30–60 bulk mole percent of the ore-forming fluids at the Alaska-Juneau mine (Leach, Goldfarb, and Hofstra, 1987). H_2O-rich and CO_2-rich inclusions, interpreted as being coevally trapped, represent immiscible fluids trapped in a boiling system. A minimum trapping pressure of 1.5 Kb, a minimum depth of emplacement of 5.5 km, and a minimum trapping temperature of 230 °C were determined from the intersection of isochores for the two types of fluid inclusions (Goldfarb and others, 1986). The intense hydrofracturing of the metasedimentary host rocks, which contributed to the development of abundant quartz-carbonate veins at the Alaska-Juneau south pit, was probably caused by fluid immiscibility (boiling) of the mineralizing fluids (Leach, Goldfarb, and Light, 1987).

A preliminary oxygen-isotope study yielded $\delta^{18}O$ values ranging from +17.1 per mil to +18.1 per mil for quartz vein material from the Alaska-Juneau mine (four samples). Assuming isotopic equilibrium between quartz and fluid at a minimum temperature of 230 °C for deposition of the vein quartz, the hydrothermal fluids that produced the deposit would have had $\delta^{18}O$ values in the range of +6 to +8 per mil, which is within the range of values inferred for primary magmatic waters (Taylor, 1979). However, if temperatures of deposition of vein quartz significantly exceeded 230 °C, the $\delta^{18}O$ of hydrothermal fluids would be greater than the maximum value of +9 per mil for primary magmatic waters. Fluids with $\delta^{18}O$ in the range of +9 to +11 per mil, which would result from temperatures of deposition in the vicinity of 300 °C, match the range of values for waters isotopically equilibrated with volcanic rocks, volcanogenic sediments, or graywackes under greenschist- to amphibolite-facies conditions (+5 to +13 per mil; Taylor, 1979; Fyfe and Kerrich, 1984). Analyses of hydrothermal sericite from the Alaska-Juneau mine give δD values of –61 per mil and calculated values for fluids in equilibrium of –20 to –30 per mil. These values fall well within the metamorphic water field (R.J. Goldfarb, written commun., 1988).

The age of mineralization at the Alaska-Juneau South pit is believed to be about 55.3±2.1 Ma, based on a K-Ar age of sericite from a gold-bearing vein (Goldfarb and others, 1987). This age is supported by a Rb-Sr isochron at 57 Ma on vein materials (Rainer Newberry, written commun., 1987). Because the gold-bearing quartz veins cut the metamorphic foliation in the slates and phyllites, the maximum age of mineralization in the A-J system is also constrained by the age of the metamorphism, which has been dated at 57–60 Ma by U-Pb and K-Ar techniques (Newberry and Brew, 1988). The tonalite sill of the western Coast plutonic-metamorphic complex (Brew and Ford, 1984b) has been dated at about 67 Ma (Gehrels and others, 1984); it was emplaced shortly after the peak of metamorphism in the area of most intense deformation (Brew and others, 1976; Brew and Ford, 1984b). Compression related to the emplacement of the tonalite sill continued until approximately 60 Ma. Emplacement of the mineralized quartz veins in fractures was postkinematic and followed relaxation of the compressional stress field, and therefore the maximum age of the A-J system must be less than 60 Ma. Igneous rocks dated at 50 Ma (Gehrels and others, 1984) in the Juneau vicinity were emplaced at relatively shallow levels, compared with minimum vein emplacement depths of 5.5 km determined from fluid inclusion trapping conditions (Leach and others, 1986; Leach, Goldfarb, and Light, 1987), suggesting that these intrusions are younger than the veins and thus constrain the minimum age of the mineralizing system.

TREADWELL SYSTEM

The mines in the Treadwell system are in a series of altered and mineralized albite diorite sills that intrude the Seymour Canal Formation along the contact between the black slates that form the footwall (Treadwell Slate) and a greenstone unit that forms the hanging wall (Spencer, 1905). The black slates of the Seymour Canal Formation contain abundant carbonaceous material and are Jurassic to Cretaceous in age (Brew and Ford, 1977). In general, the foliation in the Seymour Canal Formation trends northwest, parallel to the regional structure, and dips about 50°–70° NE. Locally the slate beds have been distorted into small folds a meter or so across, probably formed during the intrusion of the diorite sills (Twenhofel, 1952). The greenstone, which forms the hanging wall of the ore deposits, is about 100 m thick, and is a highly altered diabase or andesite. It is locally schistose, and follows the strike and dip of the foliation in the encompassing slates (Spencer, 1905).

The mineralized diorite sills are several kilometers long and more than a hundred meters thick, and they parallel the regional structure. They are composed mainly of albite, calcite, and quartz, with lesser amounts of biotite, chlorite, epidote, hornblende, magnetite, pyrite, pyrrhotite, rutile, sericite, stibnite, and zoisite (Spencer, 1905). Intrusion of the sills into the Treadwell slate caused the development of some hornfels texture, but contact aureoles are limited in areal extent (Twenhofel, 1952).

Ore zones in the Treadwell system consist of base and precious metals disseminated (1) in the albite diorite sills and (2) in reticulated veins and stringers of calcite and quartz from a few millimeters to a few centimeters in width and constituting about one-fifth of the volume of the sills (Spencer, 1905). Calcite, by far the most abundant mineral, occurs in the veins and stringers and is disseminated throughout the sills. Disseminated quartz rarely occurs in the sills and is restricted essentially to the veins and stringers. Calcite commonly occurs without quartz, but where both minerals occur in the same veinlet, calcite normally occupies the border of the quartz veinlet and is disseminated into the sill rock (Spencer, 1906). Locally, gold-bearing veins and stringers extend out into the slates that form the footwall of the mineralized albite diorite sills (Spencer, 1905).

Three different types of ore have been recognized in the Treadwell system: (1) "white ore" is the most abundant and consists of mineralized and altered albite diorite sill rock; (2) "mixed ore" is formed where small fine-grained sills and stringers of albite diorite have pervaded the slate and where sulfides are disseminated throughout both the slate and sills; (3) "brown ore" is altered and mineralized slate adjacent to the sills and represents a minor portion of the total production (Spencer, 1905, 1906).

Metallic minerals constitute about 2 percent of the Treadwell ores. Pyrite, the most abundant sulfide, both is disseminated throughout the sill and occurs in the veinlets. Gold, chalcopyrite, galena, sphalerite, molybdenite, native arsenic, realgar, and orpiment have all been observed in small quantities (Spencer, 1905). Because the gold is irregularly distributed throughout the albite diorite sills, the major control of ore localization was probably the fracture-induced permeability of the rock. In general, higher gold concentrations tend to be associated with a greater density of quartz and calcite veinlets (Spencer, 1905). Although 60–75 percent of the gold is free milling, visible gold is rare in both the sill rock and the veinlets. Some of the gold is associated with the pyrite, but the distribution of pyrite and the distribution of gold seem to be largely independent (Spencer, 1905).

A preliminary oxygen-isotope study yielded $\delta^{18}O$ values ranging from +16.3 to +20.8 per mil for quartz-calcite-albite vein material from the Treadwell system. Values of δD of –62 per mil for hydrothermal chlorite yield calculated values of –20 to –30 per mil for fluids in equilibrium, and fall well within the metamorphic water field (R.J. Goldfarb, written commun., 1988). These values suggest that temperatures of vein deposition and isotopic composition of fluids were similar to those at the A-J system, and that the mineralizing fluids were released during metamorphism of rocks subducted beneath the Coast Mountains.

Neither the age of the albite diorite sills nor the age of mineralization in the Treadwell system is known. The sills may be as old as or younger than a 90 Ma intrusive event known from northeastern Admiralty Island, some 25 km to the southwest. The sills are not foliated and therefore postdate the major regional metamorphism of the adjacent rocks. Regional studies show that the Seymour Canal Formation, which is Late Jurassic and Early Cretaceous in age (Loney, 1964), underwent low-grade greenschist facies dynamothermal metamorphism sometime before 100 Ma. Metamorphism associated with the deformation of the Perseverance slate (62–69 Ma) overprints the effects of the earlier metamorphic event, and the two may not be distinguishable in the vicinity of the Treadwell system. The maximum age of mineralization in the Treadwell system is therefore interpreted to be no older than 90 Ma and may be younger than 60–69 Ma. The similarity in isotopic composition and paragenesis between the Treadwell and A-J systems suggests that the Treadwell system is equivalent in age to the A-J system.

CONCLUSIONS

The A-J (Alaska-Juneau) system is restricted to a 6-km-long zone in the lowest 100 m of the carbonaceous Perseverance Slate, just above the greenstones of the Gastineau Volcanic Group. The highest gold concentrations are found in quartz veins and stringers near where altered amphibolite lenses finger out into the slate. The slate has both well-developed joint sets and a locally well developed axial plane cleavage. These relationships suggest that lithology and permeability were important factors in localizing ore deposition.

The Treadwell system occurs as reticulated veins and stringers in a highly fractured albite diorite sill 70 m wide and 3 km long. Gold is disseminated throughout the sill and also is hosted in calcite and quartz veins and stringers cutting the dike and footwall slates. The placement of the albite diorite sill between ductile greenstone and slate walls probably intensified the fracturing of the sill and greatly increased the permeability, which contributed to the localization and concentration of the ores.

The postmetamorphic intrusive rocks of the Coast plutonic-metamorphic complex have been thought to be related to the genesis of gold deposits in the Juneau gold belt (Dawson, 1889; Spencer, 1906). Twenhofel and Sainsbury (1958) postulated that mineralization in the Juneau gold belt was spatially related to prominent northwest-trending features, one of which is known as the Coast Range megalineament (Brew and Ford, 1978); the megalineament is interpreted to represent the surface expression of the buried contact between the slates, phyllites, and greenstones to the southwest and the more coarsely crystalline plutonic and metamorphic rocks to the northeast. The location of the A-J and Treadwell systems on either side of this major lineament suggests that it had some regional influence on the migration of ore fluids. Ore distributions in both the A-J and Treadwell systems suggest that the mineralization was postkinematic and structurally controlled, and because the age of regional metamorphism may be the same at both deposits, both systems may have formed at about the same time.

The tonalite sill body closest to the the A-J deposit is well foliated and is enclosed in highly deformed rocks. It is currently interpreted to be prekinematic in relation to the major compressive deformation, while slightly more distant tonalite sill bodies are younger and are late synkinematic with respect to the regional metamorphism (Ford and Brew, 1981). The more distant sill bodies have been dated at 62–67 Ma (Gehrels and others, 1984). The fractures along which the mineralizing fluids were channeled were developed in a noncompressive regime, and postdate the regional metamorphism, both types of tonalite sill bodies, and also the slightly foliated plutons northeast of the tonalite sill that are dated at about 60 Ma (Gehrels and others, 1984). Nearby, 50 Ma intrusions are relatively shallow, based on regional considerations. The estimated emplacement depths of these intrusions are less than those inferred from the study of fluid inclusions in vein material. Still younger intrusions known to occur elsewhere in the Coast Mountains have been dated at about 20 Ma; they are very shallow and certainly postdate the mineralization. These relations are interpreted to limit the age of mineralization at the A-J deposit between 60 Ma and 50 Ma.

During the interval from 56 to 43 Ma, the relative motion along the western margin of southeastern Alaska changed from strongly convergent, with the northeasterly subduction of the Kula Plate at about 120 km/m.y., to transpressive, with the northward migration of the Pacific plate at about 40 km/m.y. (Engebretson and others, 1985). If the mineralization of the A-J and Treadwell systems occurred at about the same time, then both systems probably developed early in this period and were accompanied by uplift of the Coast Mountains. Relaxation of the regional stress field allowed the influx of large volumes of hydrothermal fluids from depth. The rapid migration of fluids caused intense fracturing in the more competent amphibolite lenses in the A-J system and in albite diorite sills in the Treadwell system. Significant decrease in the confining pressure and temperature also promoted boiling of the fluids and precipitation of metals to form the A-J and Treadwell deposits.

Manuscript received by scientific editors February 1986

REFERENCES CITED

Barton, C.C., and Light, T.D., 1987, Structural fabric analysis of the Perseverance slate and gold-bearing quartz veins in the south ore body of the Alaska-Juneau lode system, southeastern Alaska, *in* Hamilton, T.D., and Galloway, J.P., eds., Geologic studies in Alaska by the U. S. Geological Survey during 1986: U.S. Geological Survey Circular 998, p. 110–112.

Berg, H.C., 1984, Regional geologic summary, metallogenesis, and mineral resources of southeastern Alaska: U.S. Geological Survey Open-File Report 84–572, 298 p.

Bohlke, J.F.P., 1982, Orogenic (metamorphic-hosted) gold-quartz veins, *in* Erickson, R.L., 1982, Characteristics of mineral deposit occurrences: U.S. Geological Survey Open-File Report 82–795, p. 62–68.

Brew, D.A., and Ford, A.B., 1977, Preliminary geologic and metamorphic-isograd map of the Juneau B–1 quadrangle, Alaska: U.S. Geological Survey Miscellaneous Field Studies Map MF–846, scale 1:31,680.

_____ 1978, Megalineament in southeastern Alaska marks southwest edge of Coast Range batholithic complex: Canadian Journal of Earth Science, v. 15, p. 1763–1772.

_____ 1984a, The northern Coast plutonic complex, southeastern Alaska and northwestern British Columbia, *in* Coonrad, W.L., and Elliott, R.L., eds., The United States Geological Survey in Alaska—Accomplishments during 1981: U.S. Geological Survey Circular 868, p. 120–124.

_____ 1984b, Timing of metamorphism and deformation in the Coast plutonic-metamorphic complex, near Juneau, Alaska: Geological Society of America Annual Meeting, Cordilleran Section, 80th, Anchorage, Alaska, May 30–31, June 1, 1984, Abstracts with Programs, v. 16, no. 5, p. 272.

_____ 1985, Preliminary reconnaissance geologic map of the Juneau, Taku River, Atlin, and part of the Skagway 1:250,000 quadrangles, southeastern Alaska: U.S. Geological Survey Open-File Report 85–395, 23 p.

Brew, D.A., Ford, A.B., Grybeck, D., Johnson, B.R., and Nutt, C.J., 1976, Key foliated quartz diorite sill along southwest side of Coast Range complex, northern southeastern Alaska, *in* Cobb, E.H., ed., The United States Geological Survey in Alaska—Accomplishments during 1975: U.S. Geological Survey Circular 733, p. 60.

Cox, D.P., and Singer, D. A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Dawson, G.M., 1889, Notes on the ore deposit of the Treadwell mine, Alaska: American Gemologist, v. 4, p. 84–88.

Engebretson, D.C., Cox, Allan, and Gordon, R.G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin: Geological Society of America Special Paper 206, 59 p.

Ford, A.B., and Brew, D.A., 1981, Orthogneiss of Mount Juneau—An early phase of Coast Mountain plutonism involved in Barrovian regional metamorphism near

Juneau, *in* Albert, N.R.D., and Hudson, Travis, eds., The United States Geological Survey in Alaska—Accomplishments during 1979: U.S. Geological Survey Circular 823–B, p. B99–B102.

Fyfe, W.S., and Kerrich, R., 1984, Gold—Natural concentration processes, *in* Foster, R.P., ed., Gold '82, The geology, geochemistry, and genesis of gold deposits: Rotterdam, A.A. Balkema, p. 99–127.

Gehrels, G.E., Brew, D.A., and Saleeby, J. B., 1984, Progress report on U–Pb (zircon) geochronologic studies in the Coast plutonic-metamorphic complex east of Juneau, southeastern Alaska, *in* Reed, K.M., and Bartsch-Winkler, Susan, eds., The United States Geological Survey in Alaska—Acomplishments during 1982: U.S. Geological Survey Circular 939, p. 100–102.

Goldfarb, R.J., Leach, D.L., Light, T.D., Patterson, C.J., Pickthorn, L.B., and Pickthorn, W.J., 1987, The Juneau gold belt—A mother lode-type deposit in southeastern Alaska: Geological Society of America Abstracts with Programs, v. 19, no. 6, p. 382.

Goldfarb, R.J., Light, T.D., and Leach, D.L., 1986, Nature of the ore fluids at the Alaska-Juneau gold deposit, *in* Bartsch-Winkler, Susan, and Reed, K.M., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1985: U.S. Geological Survey Circular 978, p. 92–95.

Leach, D.L., Goldfarb, R.J., and Hofstra, A.H., 1987, Fluid inclusion characteristics of the Juneau gold belt, southeastern Alaska: Geological Society of America Abstracts with Programs, v. 19, no. 6, p.398.

Leach, D.L., Goldfarb, R.J., and Light, T.D., 1987, Fluid inclusion constraints on the genesis of the Alaska-Juneau gold deposit, *in* Elliott, I.L., and Smee, B.W., eds., Geoexpo/86: Exploration in the North American Cordillera, Association of Exploration Geochemists, Ontario, Canada, p. 150–159.

Leach, D.L., Light, T.D., and Goldfarb, R.J., 1986, Fluid-inclusion constraints on the genesis of the Alaska-Juneau gold deposit [abs.]: Association of Exploration Geochemists Annual Meeting, Vancouver, Canada, May 12–14, 1986, p. 53–54.

Loney, R.A., 1964, Stratigraphy and petrography of the Pybus-Gambier area, Admiralty Island, Alaska: U.S. Geological Survey Bulletin 1178, 103 p.

Newberry, R.J., and Brew, D.A., 1987, The Alaska-Juneau gold deposit; remobilized syngenetic versus exotic epigenetic origin, *in* Hamilton, T.D., and Galloway, J.P., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1986: U.S. Geological Survey Circular 998, p. 128–131.

_____ 1988, Alteration zoning and origin of the Alaska-Juneau gold deposit, *in* Galloway, J.P., and Hamilton, T.D., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1987: U.S. Geological Survey Circular 1016.

Scott, W.P., 1932, Milling methods and ore-treatment equipment: Engineering and Mining Journal, v. 133, p. 475–482.

Smith, P.S., 1941, Fineness of gold from Alaska placers: U.S. Geological Survey Bulletin 910–C, p. 147–272.

Spencer, A.C., 1905, The Treadwell ore deposits, Douglas Island: U.S. Geological Survey Bulletin 259, p. 69–87.

_____ 1906, The Juneau gold belt, Alaska: U.S. Geological Survey Bulletin 287, 137 p.

Stone, D., and Stone, B., 1980, Hard rock gold—The story of the great mines that were the heartbeat of Juneau: City and Borough of Juneau Centennial Committee, Juneau, Alaska, 108 p.

Taylor, H.P., 1979, Oxygen and hydrogen isotope relationships in hydrothermal mineral deposits, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits, 2nd edition: New York, John Wiley, p. 236–277.

Twenhofel, W.S., 1952, Geology of the Alaska-Juneau lode system, Alaska: U.S. Geological Survey Open File Report 52–160, 180 p.

Twenhofel, W.S., and Sainsbury, C.L., 1958, Fault patterns in southeastern Alaska: Geological Society of America Bulletin, v. 69, p. 1431–1442.

Wayland, R.G., 1939, Geology of the Juneau region, Alaska, with special reference to the Alaska Juneau ore body: Minneapolis, Minn., University of Minnesota Ph. D. thesis, 93 p.

_____ 1960, The Alaska Juneau gold ore body: Neues Jahrbuch fur Mineralogie Abhandlungen, v. 94, p. 267–279.

Wells, D.E., Pittman, T.L., Brew, D.A., and Douglass, S.L., 1985, Map and description of the mineral deposits in the Juneau, Taku River, Atlin, and part of the Skagway quadrangles, Alaska: U.S. Geological Survey Open-File Report 85–717, 332 p.

Wernecke, L., 1932, Geology of the ore zones: Engineering and Mining Journal, v. 133, p. 494–499.

☆U.S. GOVERNMENT PRINTING OFFICE:1990-773-047/6027

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879- 1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962- 1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971- 1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.

DeWitt, Light, and others—GOLD IN METAMORPHIC ROCKS, I—U.S. Geological Survey Bulletin 1857–D