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PRECAMBRIAN ORE DEPOSITS OF ARIZONA

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ABSTRACT

This paper reviews the general geologic setting of Precambrian orebodies found within Arizona, presents examples of the principal deposits and their theories of origin, and consolidates production statistics. Precambrian ore deposits have yielded significant amounts of copper, zinc, lead, gold, and silver as well as lesser amounts of tungsten, lithium, uranium, iron, microcline, and asbestos. Most of the productive portion of the exposed Precambrian is restricted to a northwest-southeast corridor of outcrops across central Arizona. Early Proterozoic volcanogenic massive sulfide deposits, mainly found in Yavapai County, have yielded direct-smelting ores that contributed most of the Precambrian ore production. The massive sulfide ores are associated with sericite-, Mg-chlorite-, and silica-altered siliceous volcanic rocks of the Yavapai Series (1740 to 1790 Ma). Copper-rich ore from Jerome and zinc- and lead-rich ore from Humboldt provided an estimated 92.5 percent of the state's 46,647,267+ short tons of massive sulfide production. Many Early Proterozoic volcanogenic massive sulfide districts also contain relatively small, closely associated precious-metal vein or hydrothermally enriched exhalative deposits.

The nonvolcanogenic Precambrian vein deposits (tungsten, uranium, and asbestos) occur in small orebodies of Middle Proterozoic age. Microcline, lithium minerals, and minor rare-earth mineral concentrations are associated with pegmatites that intrude Early Proterozoic crust. Middle Proterozoic lateritic iron ore has been mined in Gila and Navajo Counties, but Early Proterozoic taconite-type banded iron formations found in Maricopa and Yavapai Counties have never been exploited.

Only minor amounts of Precambrian ores have been mined since the early 1970s, but future precious-metal and uranium ore production appears certain. Theoretical future discoveries of concealed massive sulfide ore targets await a less certain economic outlook, despite the speculation that they may contain the greatest overall Precambrian mineral potential.

INTRODUCTION

Precambrian ore deposits in Arizona have yielded significant amounts of copper, zinc, lead, gold, and silver as well as lesser amounts of tungsten, lithium, uranium, iron, microcline, and asbestos. Production reached its peak level during the first half of this century but was followed by a steady decline as the known orebodies were depleted prior to the 1970s. Except for occurrences with significant precious-metal values, few Precambrian ores are being mined today in Arizona. The depletion of these deposits coincided with increased production from Laramide porphyry copper deposits. Depressed metal prices had slowed the exploration for concealed ore deposits by the mid-1980s.

Ores of Precambrian age principally came from Early Proterozoic massive sulfide deposits, most of which were found in the Yavapai Series rocks of central Yavapai County. The ore-related volcanic rocks were originally dated at 1760 to 1820 Ma by Anderson and others (1971). However, revised decay constants suggest that a 1740- to 1790-Ma age is more realistic (Karlstrom and Conway, 1986). Other massive sulfide deposits have been found in rocks suspected to be similar in age in Mohave, Gila, and

Maricopa Counties. The greatest share of metal production came from the copper-rich ores of the Verde district at Jerome and from zinc- and lead-rich ores of the Big Bug district near Humboldt. These two districts produced an estimated 92.5 percent of all massive sulfide ore tonnage and most of the copper, zinc, lead, gold, and silver from this ore type. Closely associated vein deposits, containing variable amounts of copper, lead, gold, and silver, appear to be genetically related to the volcanogenic massive sulfide bodies, but this relationship is not always clear-cut.

Figure 1 shows the principal Precambrian base- and precious-metal mining districts in Arizona. Most of the deposits within these districts are believed to be hosted by Early Proterozoic silicic volcanic rock suites. The district names, ages of mineralization, and classifications of ore as shown in figure 1, and also in table 1, are adapted from the usage established by Keith and others (1983) and Welty and others (1985). The following synopsis of Precambrian ore deposits of Arizona is intended to consolidate diversified reference material, present geological interpretations of individual orebodies and assess their economic worth, and speculate on future exploration potential.

The regional setting of massive sulfide ore deposits in central Arizona has been reviewed by Donnelly and Hahn

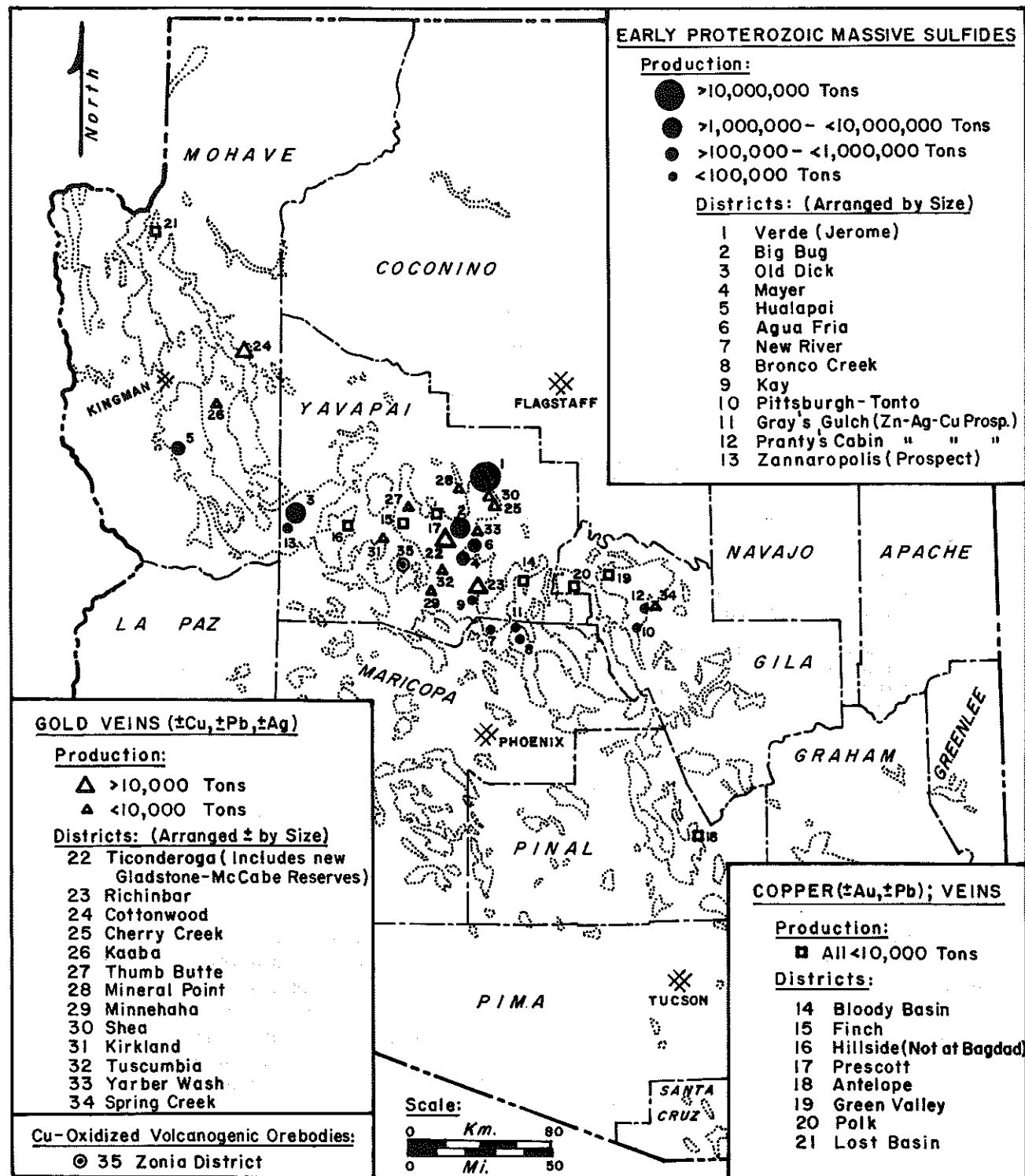


Figure 1. Location map of outcropping Early Proterozoic rocks in Arizona (dotted outline), which shows principal base- and precious-metal mining districts of Precambrian age. Ore classification and age of deposit are largely adapted from the usage established by Keith and others (1983) and Welty and others (1985).

TABLE 1: Precambrian Volcanogenic Massive Sulfide District Production in Arizona (Data from Keith and others, 1983, unless noted)

District Name	County	Tons Produced	Pounds Cu	Pounds Pb	Pounds Zn	Ounces Au	Ounces Ag	Active
Verde ^a	Yavapai	37,098,755+	3,625,051,000	693,000	97,352,000	1,579,000	57,313,000	1893-1975
Big Bug ^b	Yavapai	6,033,912+	22,656,000+	287,433,000+	838,370,000+	693,450+	20,626,000+	1902-1968
Old Dick ^c	Yavapai	1,730,000±	120,000,000±	3,100,000±	414,000,000±	3,600±	670,000±	1917-1977
Mayer ^d	Yavapai	1,424,000	92,000,000	—	—	71,600	1,786,000	1896-1972
Hualapai	Mohave	161,000	7,247,000	897,000	11,370,000	700	99,000	1918-1970
Agua Fria	Yavapai	160,000	11,600,000	3,000	16,000	900	48,000	1901-1969
New River	Maricopa	34,000	1,304,000	—	—	500	14,000	1901-1968
Bronco Creek	Maricopa	3,000	109,000	—	—	600	500	1930s
Kay	Yavapai	2,600	296,000	13,000	—	150	2,700	1910-1966
Pittsburgh-Tonto	Gila	10±	500	100	—	—	—	1917
Gray's Gulch	Maricopa	(Zn-Ag-Cu prospect, no known production)						
Pranty's Cabin	Gila	(Zn-Ag-Cu prospect, no known production)						
All Districts		46,647,267+	3,880,263,500+	292,139,100+	1,361,108,000+	2,350,500+	80,559,200+	1893-1977

Notes: ^aCompiled from Phelps Dodge Corp. and Verde Exploration Co. data.; see table 2.
^bUses only the statistics for the Iron King mine by Lawrence and Dixon (1986).
^cRefer to table 3.
^dIncludes Blue Bell mine estimate, but excludes Desoto mine production.

(1981). Because of their paramount economic importance, volcanogenic ore systems will be described in most detail in this summary. Attention will be given to individual orebodies on the basis of relative worth, or because of some unusual characteristic of the deposit. The Precambrian tungsten, uranium, iron, asbestos, and pegmatite-related ore deposits will also be discussed briefly.

PRECAMBRIAN OUTCROP LIMITATIONS

The distribution of Precambrian rocks that host important orebodies is highly irregular in outcrop pattern because of a number of factors. Except for a narrow exposure in the bottom of the Grand Canyon, the northeastern half of the state is completely covered by the Phanerozoic rocks of the Colorado Plateau. The southwestern part of the state is dominated by younger terrane, and the sporadic Precambrian outcrops that do occur contain few ore deposits of that age. Outcrops that contain the greatest economic potential are confined to a partially exposed, broad belt that trends diagonally across Arizona from the northwest to the southeast corner. Within this belt most ore deposits are located in central Yavapai County where outcrops of Early Proterozoic Yavapai Series rocks are abundant.

At Jerome, Paleozoic strata crop out within 750 feet of the United Verde massive sulfide deposit, and they are also faulted against the Precambrian host rocks within 1,000 feet of the orebody on its northeast side. The adjacent United Verde Extension (U.V.X.) deposit remained hidden beneath cover rocks until its discovery in 1914. It is quite probable that if the larger body had not cropped out in such close proximity, exploration for the U.V.X. deposit would not have been initiated. The fact that two of Arizona's richest orebodies lie so close to the onlapping Phanerozoic cover is one reason why exploration activities

remain stimulated in the Verde district. In addition to the Paleozoic sedimentary rock and Tertiary volcanic cover, large areas of potentially important Precambrian terrane remain hidden beneath a cover of relatively young lake beds and alluvium.

MINERAL PRODUCTION FROM PRECAMBRIAN ORE DEPOSITS

This section contains several tables that list ore and metal production figures for selected ore types and districts. All weights and measures used in this summary are as reported by the mines during the time of mining. Unless otherwise specified, the values are given in short tons, pounds, troy ounces, miles, and feet. Table 1 lists the production from ten of the most important massive sulfide districts, and figure 2 shows a comparison of the tonnage, copper, and zinc produced from these districts. Although the Verde district produced most of the tonnage and copper values, the Big Bug and Old Dick districts produced most of the zinc.

Tables 2 and 3 show the production statistics for the large deposits of the Verde district at Jerome and the Old Dick district near Bagdad. Table 4 lists the more important non-massive sulfide vein deposits of the copper-rich and precious-metal-rich varieties, as well as the major tungsten occurrences found in the older rocks. Much of the statistical base for these districts and deposits came from Keith and others (1983), with other important additions as noted.

CHANGING THEORIES OF ORE GENESIS

Theories on the genesis of certain metallic orebodies have undergone radical revisions during the past century and particularly within the last several decades. An

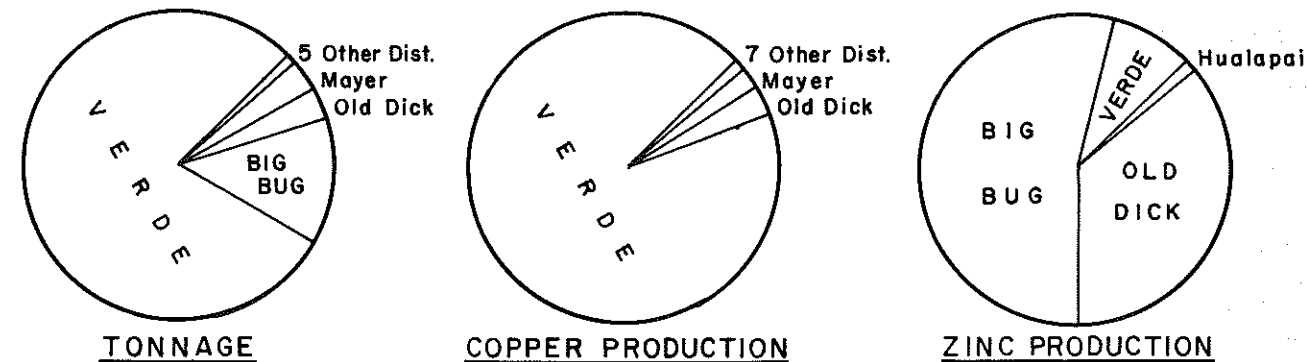


Figure 2. Comparison of ore tonnage and copper and zinc production from massive sulfide districts in Arizona from 1893 to 1977 (excludes possible reserves). The greatest contrast between districts can be seen in the dramatic difference in the metal content of the ores from the Verde and Big Bug districts, based on the metals produced. The Verde ores show the following metal ratios: Cu/Pb=5,230, Cu/Zn=37, and Ag/Au=36. The Big Bug ores show metal ratios of: Cu/Pb=0.08, Cu/Zn=0.03, and Ag/Au=30. Ores from the Old Dick and Hualapai districts are zinc rich but contain appreciable copper as well and appear to be intermediate between the Verde and Big Bug ore types.

excellent example of the changing concepts can be seen in the theories of origin of massive sulfide ore deposits that played a vital role in the historic development of Arizona. During the peak levels of production it was almost universally accepted that these deposits were the product of hydrothermal replacement of a preexisting host rock. The delicately banded, tabular massive sulfide ores at the Iron King mine near Humboldt were "attributed to pseudomorphism of various older structures such as bedding, fracture, and foliation" by Anderson and Creasey (1958, p. 164). However, Gilmour and Still (1968) announced a major breakthrough by concluding that the Iron King ores were the product of submarine hot springs that precipitated the sulfides directly onto the volcanic sea floor. Starting in the late 1960s a growing number of exploration geologists throughout the world began to accept the volcanogenic model to explain most massive sulfide ore deposit origin (Sangster, 1972).

Anderson and Creasey (1958) also described the ore deposits of the Verde district at Jerome. Their conclusions

at that time mirrored the work of many eminent predecessors in concluding that the large massive sulfide body had been formed by selective hydrothermal replacement. They observed that "the bulk of the chalcopryite was not deposited until after the large bodies of black schist (chlorite rock) on the footwall side of the massive sulfide pipe were formed, and on the lower levels in particular, fractured black schist contains much chalcopryite, resulting in large and important shoots of 'schist ore'" (Anderson and Creasey, 1958, p. 98). Many of the mine geologists had observed the cross-cutting footwall veins and the replacement textures in the highest grade sections of the deposit. It was logical to assume that the entire ore system was also the product of hydrothermal replacement.

Figure 3 shows the 2,400-foot level of the United Verde mine at Jerome. This level map, thought to be representative of the central portion of the orebody, shows that much of the copper ore is located below the massive sulfide body in the chloritized Cleopatra formation. The

Table 2. Verde District Ore and Metal Production

A. Ore Production from Verde district mines

Mineral Deposit (Type of Ore)	Active Interval	Production Short Tons	% Cu	oz/t Au	oz/t Ag
United Verde (massive sulfide and F.W. "stringer veins")	1893-1953	32,784,578	4.79	0.043	1.61
Big Hole Mining Co.; United Verde (F.W. copper veins)	1954-1975	206,149	6.13	0.014	1.01
United Verde Extension (supergene-enriched chalcocite ore)	1915-1938	3,878,825	10.23	0.039	1.71
Copper Chief (sulfide ore)	1904-1905	30,000	2.17	—	—
Copper Chief (oxide ore)	1916-1918	60,000±	—	0.42±	6.2±
Verde Central (massive sulfide and "Rock Butte fracture")	1928-1930	139,203+	2.7±	?	0.4±
Cliff (massive sulfide); grade estimated from 1976 drilling	Pre-1919	Small	(4.5±)	(0.04±)	(1.6±)
All deposits; weighted average grade	1893-1975	37,098,755+	5.35	0.043	1.62

B. Estimated metal production from all Verde district mines

Copper	3,625,051,000 pounds (1,812,525 short tons)
Lead	693,000 pounds
Zinc	97,352,000 pounds
Gold	1,579,000 ounces
Silver	57,313,000 ounces

TABLE 3. Old Dick District Ore and Metal Production

A. Estimated ore production from district mines

Mineral Deposit	Active Interval	Production Short Tons	% Cu	% Zn	% Pb
Old Dick	1943-1965	676,810	3.36	10.6	?
Bruce	1968-1977	822,611	3.65	12.7	?
Copper Queen	1961-1965	140,350	4.70	14.4	?
Copper King ^a	1917-1955	80,000±	0.5±	12±	0.8±
Other deposits (Pinafore, Red Cloud, Rudkins, Queen Bee)		10,000+	?	?	?
All deposits; weighted grade		1,730,000±	3.47±	12.0±	?

B. Estimated metal production from district

Copper	120,000,000 pounds ^b (60,000 Tons)
Lead	3,100,000 pounds ^c
Zinc	414,000,000 pounds ^b
Gold	3,600 ounces ^c
Silver	670,000 ounces ^c

Notes: ^aEstimated minimum values based on 1917-1951 production figures by Anderson and others (1955, p. 85); No tons were specified; Conway (1986) gave 150,000 tons, which appears to be too high for metal produced.

^bComputed from grades given by Conway (1986).

^cExtrapolated from tonnage and grades by Keith and others (1983, p. 38-39).

TABLE 4. Other Precambrian Deposits (Non-Massive Sulfide)

A. Copper deposits, with or without gold or lead; veins

District Name	County	Active	Tons	Metal Values Produced
Green Valley	Gila	1901-1958	7,800	93,000 lb Cu, 1,400 oz Au, 5,300 oz Ag
Antelope	Pinal	1908-1922	1,000	199,000 lb Cu, <100 oz Au, 500 oz Ag
Hillside District				
Not at Bagdad	Yavapai	1930-1937	900	3,000 lb Cu, 1,300 lb Pb, 800 oz Au, 750 oz Ag
Finch	Yavapai	1936-1949	500	17,000 lb Cu, 100 oz Au, 1,000 oz Ag

B. Gold deposits, with or without copper or lead; veins

District Name	County	Active	Tons	Metal Values Produced
Tuscumbia (Mined)	Yavapai	1894-1942	850	1,700 lb Cu, 500 lb Pb, 500 oz Au, 45,800 oz Ag
Tuscumbia (McCabe-Gladstone Reserves)				(Reserves of 498,000 tons; 0.41 oz/t Au, 2.6 oz/t Ag ^b)
Richinbar	Yavapai	1905-1971	32,000	7,400 lb Cu, 7,000 lb Pb, 4,800 oz Au, 1,500 oz Ag
Cottonwood	Yavapai	1907-1968	13,500	457,000 lb Cu, 500 lb Pb, 3,000 oz Au, 6,000 oz Ag
Cherry Creek	Yavapai	1907-1948	7,000	28,000 lb Cu, 150 lb Pb, 4,000 oz Au, 6,200 oz Ag
Kaaba	Mohave	1926-1936	3,000	200 lb Cu, 41,000 lb Pb, 700 oz Au, 550 oz Ag
Thumb Butte	Yavapai	1905-1941	2,000	2,700 lb Cu, 800 oz Au, 300 oz Ag

C. Middle Proterozoic tungsten deposits; veins

District Name	County	Active	Tons	Metal Values Produced
Camp Wood	Yavapai	1940s	?	8,686 short ton units WO ₃ ^b
Tungstonia	Yavapai	?	?	7,449 short ton units WO ₃
Aquarius Mountains	Mohave	1969-1973	?	3,327 short ton units WO ₃ , 32 long tons Mn ore
Whetstone	Cochise	1955-1957	100	1,000 short ton units WO ₃ , 62 long tons Mn ore
Fluorescent	Mohave	?	?	132 short ton units WO ₃

Notes: ^aData from Stan West Mining Corp. 1985 Annual Report.

^bA short ton unit is equal to 1 percent per ton or 20 pounds.

chalcopyrite veining and coarse replaced sulfide textures seen in the base of the massive sulfide body were strong arguments in favor of a replacement origin.

A modern volcanogenic model for the formation of the massive sulfide deposits at Jerome has been described by Lindberg (1986c). As the early sulfide laminations were precipitated at the sea-floor vent site, their initial copper content is assumed to have been relatively low. With continued growth of new sulfide crusts on the upper surface of the body, the basal sulfides were subjected to additional hydrothermal attack and enrichment by late-stage chalcopyrite replacements. The uppermost, and last formed, sulfide layers are almost entirely composed of laminated pyrite that still shows primary depositional characteristics.

In retrospect, virtually all volcanogenic massive sulfide orebodies exhibit some form of late-stage hydrothermal

modification and remobilization of metal values. Proximal deposits that lie directly over vent sites generally show the greatest modification, whereas those deposited away from the vent sites (distal) commonly escape subsequent hydrothermal modification.

POSTDEPOSITIONAL MODIFICATIONS OF PRE-CAMBRIAN ORE DEPOSITS

A number of Precambrian orebodies in Arizona have become modified by subsequent processes that changed the original mineralogy and character of the primary ore. One example of a radical mineralogical change is the metamorphic modification of a volcanogenic massive sulfide body at the Antler deposit in the Hualapai district of Mohave County. Stensrud and More (1980) reported that the sulfide minerals were recrystallized and deformed. The former chloritic footwall alteration zone was

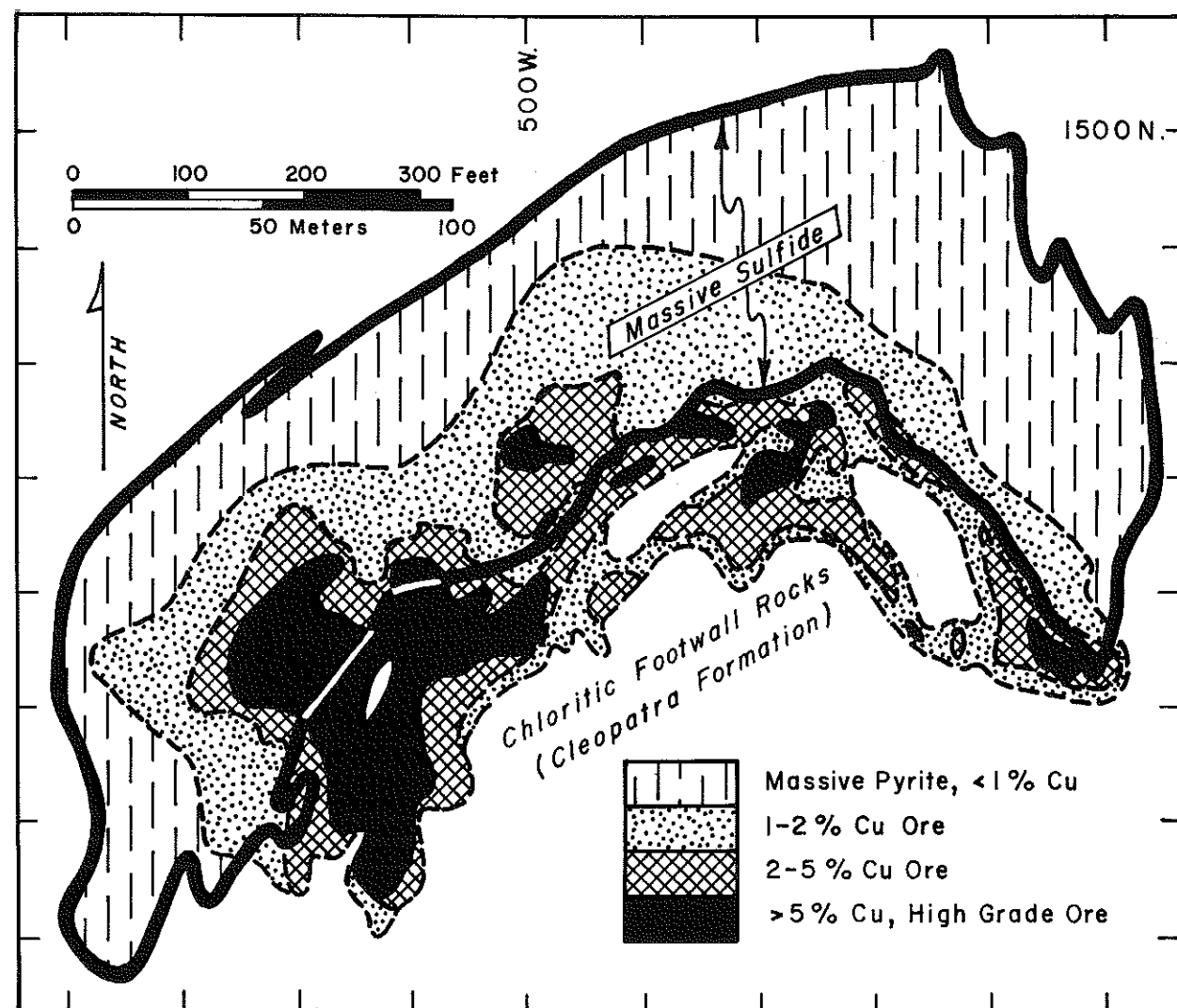


Figure 3. Plan map of the United Verde 2,400-ft level showing distribution of copper mineralization relative to the massive sulfide body. The heavy outline shows the outer boundary of the large pyritic body; the copper values in the stratigraphic hanging wall are very low. Copper mineralization is most intense at the base of the sulfide body and continues well into the chloritized Cleopatra formation footwall. It is believed that this zone of highest copper grade, which is coincident with the greatest replacement of the rhyodacite by Mg-rich chlorite, marks the fossil vent sites where hydrothermal solutions entered the base of the ore system. This figure is adapted from Anderson and Creasey (1958, fig. 17, p. 117).

converted into a fibrous Mg-silicate assemblage. Volcanic and sedimentary rocks, and perhaps some intrusive sills, were converted to gneisses, schists, and amphibolites. Stensrud and More (1980) also reported the presence of abundant pyrrhotite. Although pyrrhotite is common in many of the Archean massive sulfide deposits of the Canadian Shield, it is relatively rare in most Arizona deposits.

Virtually all massive sulfide bodies in Arizona have experienced some form of supergene enrichment or surficial oxidation. Enrichment reached an unprecedented level at the U.V.X. orebody at Jerome. In 1917 the mine produced 115,064 short tons of chalcocite-rich ore, just beneath the gossan capping, that averaged 27.5 percent copper. Although grades diminished toward the bottom of the nearly 4-million-ton orebody, the grade still averaged 10.23 percent copper over the life of the mine. The geology of this rich deposit and unusual circumstances leading to the Precambrian and Tertiary enrichment of the ores will be discussed later.

The Zonia district of Yavapai County contains several large copper oxide deposits that Keith and others (1983) have classified as part of a volcanogenic system. Oxidation has extended to depths greater than 500 feet below the surface (Lundin, 1985), but it appears that the mineralization was spread through thin lenses within the rhyolitic host rock. A computed recovery average of 0.27 percent copper from the 5.7 million tons of ore mined indicates the dispersed nature of the mineralization. It is not known whether copper grades were enriched or depleted during the oxidation process.

Concentration of gold into an economic lode deposit from an anomalous volcanogenic exhalite still remains an attractive but controversial subject. Guilbert (1981) classified the gold deposits of the Mayer area as being related to gold-bearing distal phases of iron oxide-rich exhalites. Swan and others (1982) also reported auriferous iron formation in Yavapai County. Chevillon and Norris (1986) described syngenetic gold mineralization of the volcanic and sedimentary protoliths of the metamorphic rocks of the Mojave Desert region of California and Arizona. They considered that this anomalous gold might have been the source of metal that was later remobilized into younger epigenetic deposits. It is highly probable that Precambrian volcanogenic exhalites were the sources for some of the gold that was concentrated at a later time into lode deposits or formed the parent rock from which placer deposits were derived. White (1986) has shown conclusively that volcanogenic processes were capable of depositing primary gold ore grades within siliceous domes at the U.V.X. mine at Jerome.

STRUCTURAL AND LITHOLOGIC SETTING

The structural and lithologic setting of the wide variety of Precambrian ore types is highly complex, and a complete

discussion is largely beyond the scope of this general presentation. Individual deposits will be described in some detail, but most discussions concern district-scale geology. Additional information can be obtained from the references.

A recent progress report and field guide dealing with deformational styles and lithostratigraphic sequences within the Early Proterozoic rocks of central Arizona has been presented by Karlstrom and Conway (1986). Other background material may be obtained from Donnelly and Hahn (1981) and Lindberg (1986a). Figure 4 shows the location of principal mineral deposits and major lithologic types within the area of greatest mineral production.

The dominant fold axes that are seen throughout the productive Early Proterozoic Yavapai Series rocks trend north-northeasterly in the vicinity of Mayer and Humboldt and north-northwesterly at Jerome. In between, along the so-called "Shylock Zone," the steep fold limbs trend due north-south. Complex isoclinal folding with near-vertical and subparallel fold axes and fold plunge reversals dominates the structural pattern. DeWitt (1976) has presented a detailed view of the folding in the volcanic and sedimentary rocks along the Mayer-Crown King belt. Evenson (1980) documented similar tight folds in the rocks cropping out to the north of Mayer by mapping numerous chevron-folded metachert horizons. O'Hara (1986a, 1986b) reviewed many of the previous and current mapping efforts in the Mayer-Prescott region and pointed out the controversial aspects of lithologic correlations and stratigraphic ambiguities.

The lithologic setting of massive sulfide ore deposition can vary considerably from one district to another. The copper-rich ores of the Verde district, for example, appear to favor the apex of thick rhyolitic submarine volcanic piles, with localized Mg-chlorite alteration root zones beneath a massive sulfide concentration. On the other hand, the zinc- and lead-rich ores of the Big Bug district take on a more distal, sheetlike appearance that is in harmony with the extensive and rather flat rhyolitic tuff horizons that lie in the footwall of the ore. Another radical variation within a single district appears to be one of scale. The large United Verde deposit at Jerome rests on top of a huge mass of altered siliceous crystal tuffs and flows (Cleopatra formation). Four miles southeast the small Cliff and Copper Chief deposits also lie on what is probably the thin lateral edge of the Cleopatra formation. It is assumed that the size and initial heat capacity of a newly formed eruptive mass are important factors relating to the size of any ore concentration formed on its surface.

Base- and precious-metal vein deposits are hosted in a variety of lithologic types, and their relationship to a volcanogenic setting has proved to be elusive in many examples. Some of the "veins" reported in earlier studies have turned out to be stratiform sulfide horizons. It may remain controversial as to whether the base and precious metals were introduced into a vein from an outside source

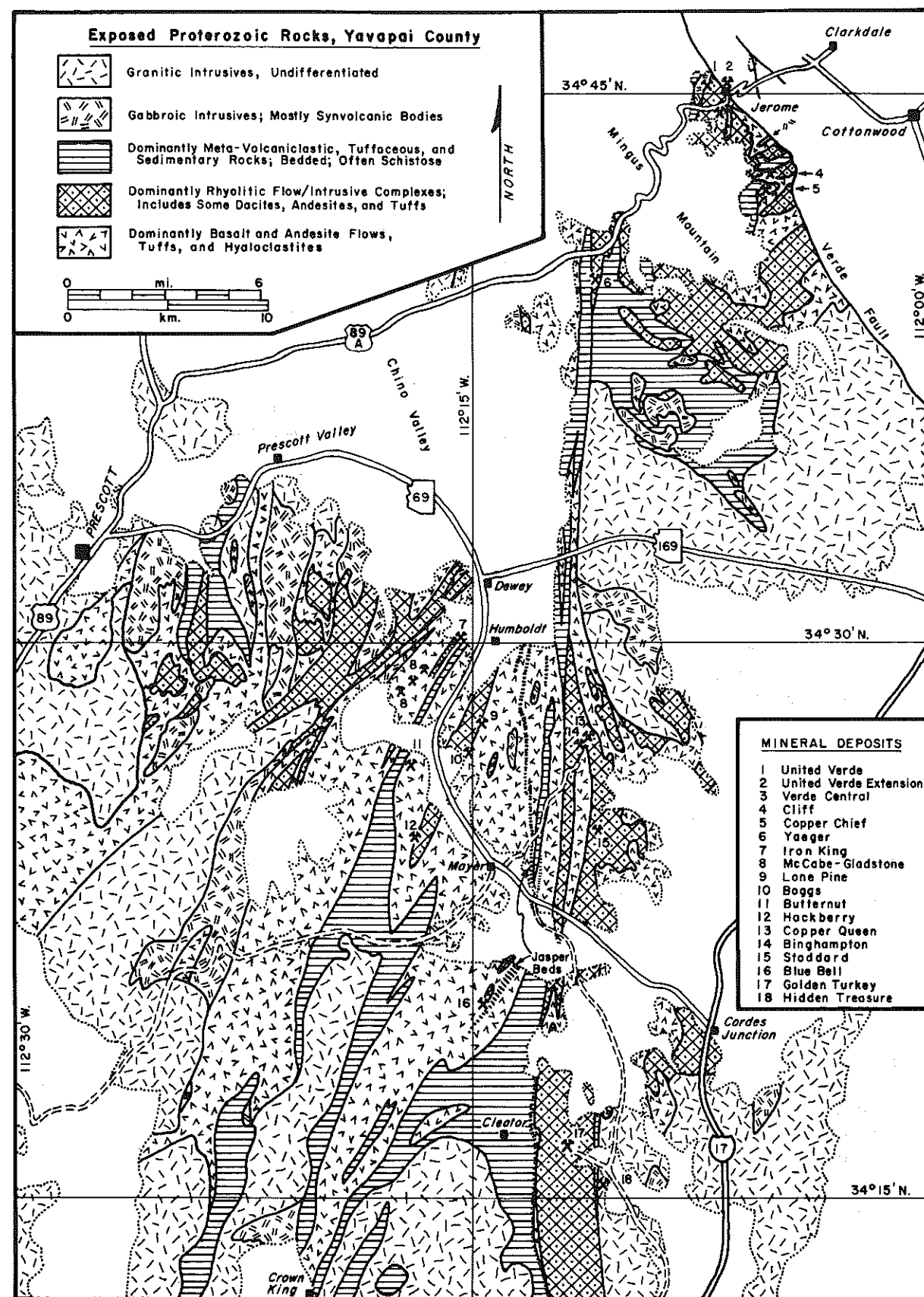


Figure 4. Ore deposits and rock types, central Yavapai County. Geology is simplified from published U.S. Geological Survey maps and private sources.

or were remobilized in situ from an anomalous exhalative source rock.

VOLCANOGENIC MASSIVE SULFIDE ORE DEPOSITS

Verde District, Jerome Area, Yavapai County

The mines of the Verde district near Jerome have produced the major share of all Precambrian ores from the southwestern United States. The district has accounted for nearly 80 percent of the tonnage mined, 93 percent of the copper, 71 percent of the silver, and 67 percent of the gold produced from Early Proterozoic massive sulfide deposits to date in Arizona (tables 1 and 2). However, zinc and lead accounted for only 7 percent and 0.2 percent, respectively, of the total state production from massive sulfide ores. Because of high copper grades in the Jerome orebodies, zinc was produced mainly as a byproduct of the mining of chalcopryite ores, and a moderate zinc reserve still remains within the United Verde deposit.

Figure 5 shows the Precambrian outcrops and location of mines in the Verde district. Figure 6 shows the surface geology of the northern part, which contained the largest deposits. The outcropping United Verde massive sulfide body was mined from 1893 to 1975 and accounted for 88.9 percent of the district production. Although the main mining operations ended in 1953, small amounts of high-grade footwall ore were mined under lease from 1954 to 1975. Supergene-enriched ores from the U.V.X. deposit remained hidden beneath Paleozoic and Tertiary cover rocks until 1914. High-grade chalcocitic ore was produced at the U.V.X. mine from 1915 to 1938 and accounted for 10.5 percent of the district tonnage. The remaining 0.6 percent came from gossan and massive sulfide ores from the Copper Chief-Equator, Cliff, and Verde Central deposits located south of Jerome. The Shea vein, which produced minor amounts of high-grade silver ore (Lindgren, 1926), is located directly south of the Copper Chief deposit but is postfolding in age and not volcanogenic in origin. Although Keith and others (1983) classified the Shea vein as Tertiary, field evidence supports a Precambrian age.

The geology and ore deposits of the Jerome area were described by Anderson and Creasey (1958). This pioneering work provided the first regional study of the Verde district and began a correlation of Precambrian rock suites between the Jerome and Mayer areas. They assigned the rocks to the Ash Creek Group of the Yavapai Series. Age dating by Silver and co-workers, as reported by Anderson and others (1971), assigned an age of 1820 Ma (now believed to be about 1790 Ma) to the Jerome area rhyolitic rocks. Most of the early workers in the camp, including Reber, Lindgren, Ransome, Norman, and others, believed that the Jerome massive sulfide deposits were the product of selective replacement of favorable host rocks. Their geological contributions are summarized by Anderson and Creasey (1958) who also concurred with the belief that the

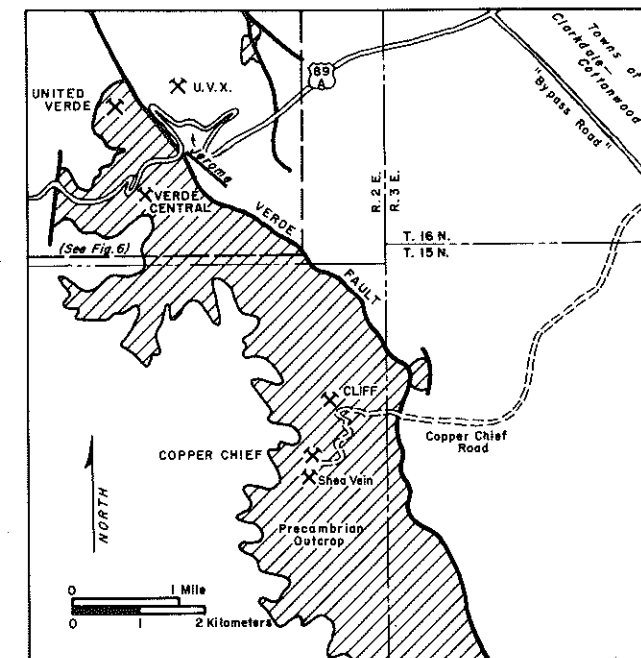


Figure 5. Location map of Precambrian rock exposures and formerly producing mines in the Verde district, Yavapai County, near Jerome, Arizona. Heavy lines show some of the Tertiary faults that are in contact with Early Proterozoic volcanic and sedimentary rock suites.

ores were of a replacement type and that a quartz porphyry intrusive rock was one of the agents responsible for ore genesis. Anderson and Nash (1972) later reinterpreted the intrusive rock to be an extrusive crystal tuff and defined it as the Cleopatra Member of the Deception Rhyolite. Gustin (1986 and 1987, personal commun.) and I prefer the informal term "Cleopatra formation" to distinguish this important ore host rock from other volcanic rocks in the Jerome succession.

Acceptance of the volcanogenic model in the Verde district was firmly established by 1971 (P. A. Handverger, 1971, personal commun.; private company reports). A brief description of the volcanogenic setting of the district was given by Lindberg and Jacobson (1974), in which the Jerome anticline was identified. The United Verde and U.V.X. orebodies lie on opposite limbs of the north-northwest-plunging fold. The long-held belief that the U.V.X. body was the downfaulted apex of the United Verde mass (Ransome, 1933) has been rejected by most workers since 1971. Handverger (1975) described the importance of the Mg-rich chlorite alteration zones associated with the U.V.X. and United Verde ore systems. Lavery (1985) identified anomalous amounts of fluorine, copper, and zinc within a zone that extends from the base of the United Verde orebody through the entire underlying Cleopatra formation and into the Deception Rhyolite. This zone is coincident with cauldron fractures, now occupied by Cleopatra feeder dikes, and with subparallel post-Cleopatra fractures associated with the venting of hydrothermal solutions during massive sulfide deposition (Lindberg, 1986c).

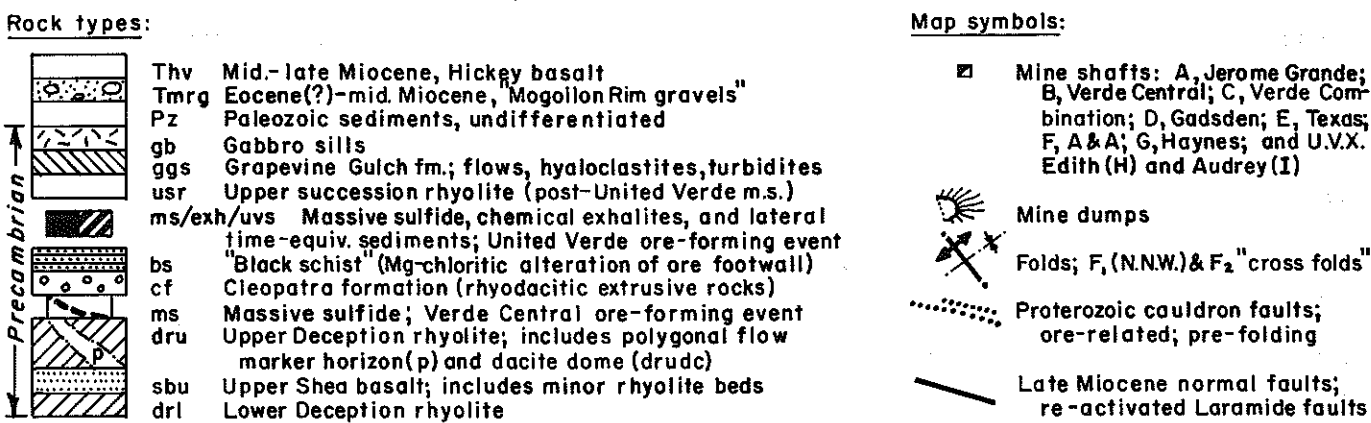
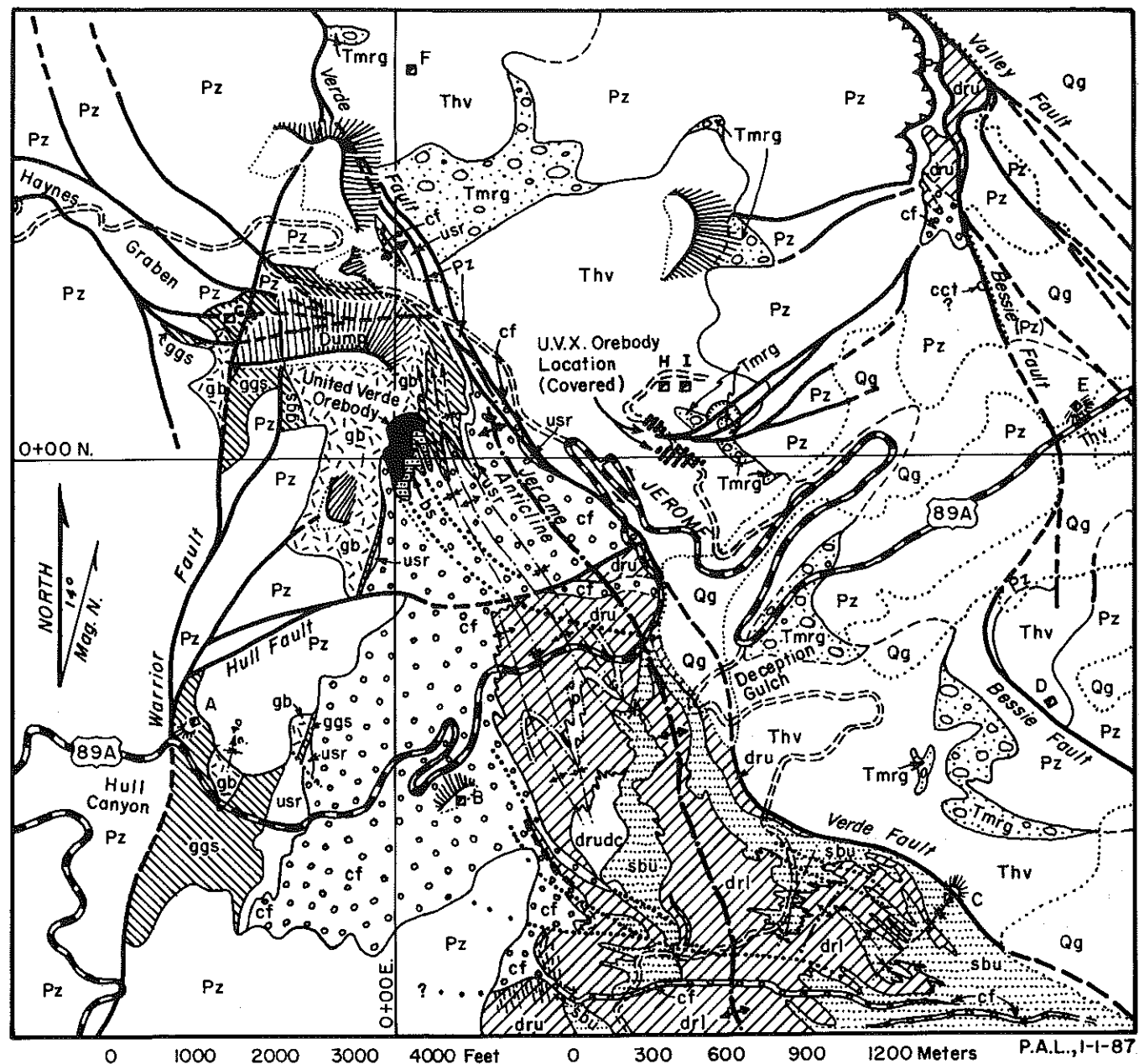


Figure 6. Geologic map of the Jerome area, Verde district, Yavapai County, Arizona. Post-1971 mapping by Lindberg (Lindberg and Jacobson, 1974; Lindberg, 1986c), Meyer (1972), and Handverger (1975) modifies the nomenclature of Anderson and Creasey (1958) and Anderson and Nash (1972). Recent studies of the Cleopatra formation by Gustin (1986, 1987, personal commun.) show it to be a rhyodacite extrusive complex.

White (1986) has described recent gold exploration activities at the U.V.X. mine. The volcanogenic system not only produced massive sulfide ores with high copper and low silica content, but also contemporaneously deposited adjacent siliceous gold ore zones that are virtually devoid of copper values.

Detailed post-1971 mapping indicates that the stratigraphic nomenclature as originally defined by Anderson and Creasey (1958) needs revision. Figure 6 shows the informal terminology in current use. Figure 7 is a cross section

through the Jerome anticline that is viewed in the direction of the north-northwest-plunging F₁ fold axes. Steep F₂ "cross folds" trend at right angles to the F₁ folds. The United Verde orebody plunges from the present surface for nearly 4,800 feet down the 60° plunge before reversing through a major cross fold near the bottom levels of the mine. The intersection of the two axial planes of the folds marks the steep ductile extension direction. During the polyphase deformation of the rock and ore system, localized ductile migration of basal chalcopiritic ore and footwall chloritic

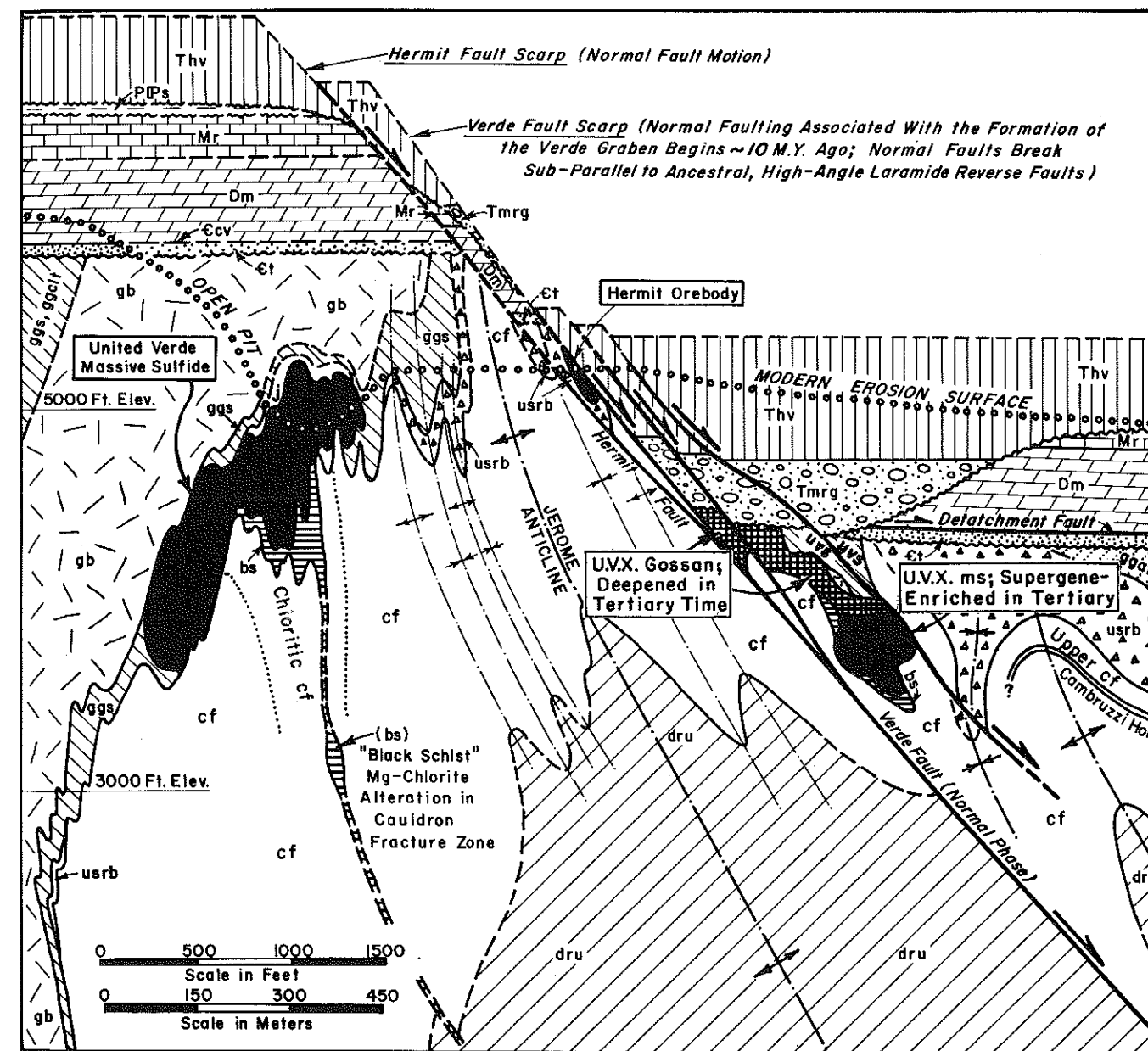


Figure 7. East-west composite cross section through the Jerome anticlinorium with the United Verde and U. V. X. orebodies located on opposite limbs. Each orebody rests on the surface of the rhyodacitic Cleopatra formation (cf) and has its own Mg-rich chlorite alteration zone. The legend for figure 6 gives the rock names and abbreviations. Postore rocks include volcanoclastic sediments, minor rhyolitic breccias and tuffs, andesitic or basaltic flows and hyaloclastites, and a synvolcanic intrusive gabbro sill. Footwall rocks show widespread sericitic alteration of feldspars and intense Mg-chlorite alteration directly below the massive sulfide ores. Failure along Laramide and late Miocene faults mirrors the F₁ fold limbs.

rocks resulted in the generation of numerous steep "ore shoots" near the base of the United Verde massive sulfide body.

A preliminary evolutionary model for the genesis of the Jerome massive sulfide ore system has been proposed by Lindberg (1986c). The Shea Basalt is located in the southern and central part of the district and is composed of massive to pillowed flows and hyaloclastites. The upper part of this basalt section is time equivalent to the basal portion of a thick rhyolitic flow and breccia accumulation near Jerome (part of the Deception Rhyolite of Anderson and Creasey, 1958). The small Verde Central ore deposit and exhalitive horizon are located at the extreme top of a thick series of rhyolite flows that are exposed in Deception Gulch just south of Jerome. At this point in the evolution of the siliceous submarine volcanic pile an abrupt cauldron subsidence, coincident with the rapid extrusion of the thick Cleopatra formation, is inferred to have occurred. The central, and highest, part of the Jerome silicic volcanic accumulation is believed to lie somewhere north of Jerome. Cleopatra extrusive rocks buried the down-to-the-north cauldron scarps that were formed in the rhyolitic substrate. The minimum volume of the Cleopatra extrusive rocks is estimated to be 6 cubic miles (25 cubic kilometers). Gustin (1988) has recently completed a study of the alteration patterns within the quartz-phenocryst-rich, rhyodacitic extrusive complex.

Soon after the Cleopatra extrusive rocks had consolidated, localized cauldron fractures once again ruptured the submarine volcanic pile. Hydrothermal solutions flowed through the fractured substrate and vented onto the sea floor as hot springs which precipitated the massive sulfide deposits. The hydrothermal cells altered a large volume of the Cleopatra formation beneath the ore zones, with conversion of feldspars to sericite. Hydrothermal Mg-chloritic alteration is also widespread in the Cleopatra footwall. The most intense "black schist" alteration is located in the roots of orebodies, where even feldspars and quartz were replaced by Mg-chlorite. As the massive sulfide deposits were being built up with laminations of pyrite, chalcopyrite, and sphalerite, the basal sulfide layers were being subjected to further hydrothermal modification (see fig. 3). When hot-spring activity began to wane, only laminated pyrite-chert was deposited near the top of the massive sulfide body. Mineralization ended with the deposition of a sulfide-free jasper caprock.

Postore basic flows, hyaloclastites, volcanoclastic sediments, and minor silicic tuff accumulations covered the orebodies and altered footwall rocks. High-level gabbro sills intruded the unaltered upper-succession rocks. The entire district was then folded with a penetrative deformation. Primary F_1 folds trend north-northwesterly and exhibit amplitudes well in excess of 6,000 vertical feet, as determined by mine exposures and deep drilling. The superimposed F_2 folds trend at right angles to the primary set and create the "egg crate" outcrop patterns and plunge reversals that are common throughout the district.

The Precambrian rocks of the Verde district were covered by a thick Paleozoic, and perhaps even a Mesozoic, section of sedimentary rocks. The first known movement on the Verde fault system is believed to have occurred during compressional Laramide uplift in this area of the Southwest. High-angle reverse motion on the ancestral Verde, Bessie, and Valley faults triggered unusual low-angle gravity faulting that removed a portion of the tilted Paleozoic strata overlying the U.V.X. deposit. Post-Laramide erosion exposed the U.V.X. gossan-sulfide body, and prolonged groundwater attack promoted additional supergene enrichment of the ores throughout Tertiary time. Hickey Basalt, dated at 10-15 Ma by McKee and Anderson (1971), capped the Tertiary conglomerate that filled a deep erosional channel cut in Paleozoic rocks directly over the U.V.X. deposit (see fig. 7). The Verde graben formed in post-Hickey time and has a collective displacement exceeding 6,100 vertical feet as revealed by 1972 Anaconda exploration drill hole AV-3. A minimum of eight major faults are known to form the southwestern graben boundary between Cottonwood and the Copper Chief mine area (Lindberg, 1983, 1986c).

The extensional faulting that formed the Verde graben exposed the Precambrian rocks of the Verde district. Modern erosion on the graben scarps has bared the slopes containing the United Verde, Verde Central, Cliff, and Copper Chief deposits to the present land surface. The small Copper Chief and Cliff orebodies lie about 4 miles southeast of Jerome and are situated at the stratigraphic top of rocks identical to the Cleopatra formation. The deposits and their host rocks appear to be scaled-down versions of the larger Jerome ore systems. I (Lindberg, 1986b) believe that the ores were formed on satellitic volcanic centers located near the outer edge of the principal Jerome volcanic pile and were formed at the same time-stratigraphic horizon.

Big Bug District, Humboldt Area, Yavapai County

The Big Bug district, located near Humboldt, was the second largest metal producer from Early Proterozoic massive sulfide deposits. The district produced nearly 13 percent of the state tonnage, 98 percent of the lead, 62 percent of the zinc, 30 percent of the gold, 26 percent of the silver, but only 0.58 percent of the copper from this type of ore. Total production amounted to more than 6 million short tons of zinc- and lead-rich ores. Most of the production came from the Iron King mine. Keith and others (1983) also listed the Boggs, Butternut, Hackberry, Huron, Iron Queen, Lone Pine, Mary Copper, Swindler, and other small mines and prospects in their tabulation on the Big Bug district. The geology of the Boggs mine area was recently described by Hurlbut (1986).

A detailed description of the mineralogy of the Iron King deposit was given by Creasey (Anderson and Creasey, 1958). He concluded that the ore formed as a vein by selective replacement of sulfides in sheared volcanic and

sedimentary lithologies. He noted the delicate mineralogic banding of pyrite, sphalerite, and lenses of quartz-ankerite. Ores generally lacked chalcopyrite but had a high content of brown sphalerite (65.3 percent zinc and 3.2 percent iron). Ubiquitous tiny grains of galena occurred in all ores, but rarely exceeded 4 percent of the total content. Tennantite was commonly associated with the galena-rich portion of the ore in areas of low pyrite content. Arsenopyrite, which displayed diamond-shaped crystal outlines, occurred in abundance in some areas of massive sulfide ore and was thought to be a replacement mineral. Silver was inferred to be in solid solution within galena and tennantite, and the gold was inferred to reside mainly with the abundant pyrite. The comment that "The greatest concentrations of precious metals also occur in quartz 'noses'" (Anderson and Creasey, 1958, p. 168) suggests that quartz and gold, along with associated ankerite, had been remobilized at a later time, perhaps during postdepositional folding and shearing. The presence of localized cross-cutting comb quartz veins, late-stage rosin sphalerite veinlets, and pseudomorphic minerals obviously influenced the belief in a replacement origin for the ores.

A more recent description of the Iron King deposit concluded that "the ore bodies were formed through the agency of volcanic hot springs on, or near, a submarine surface of deposition" (Gilmour and Still, 1968, p. 1239-1240). This innovative paper was a strong influence in bringing recognition of the volcanogenic model to the study of other massive sulfide deposits in Arizona. Figure 8 shows the surface geology of the Iron King mine area, and figure 9 depicts a composite longitudinal section through the orebody.

The host rocks in the Iron King mine area strike north-northeasterly and dip at an average of about 78° NW. The succession is overturned with stratigraphic tops facing east-southeast. The stratigraphic footwall of the ore horizon is composed of lower Spud Mountain tuff, a modification by Gilmour and Still (1968) of the original usage presented by Anderson and Creasey (1958). The stratification of the lower Spud Mountain tuff unit, going upsection, is meta-andesite, quartz-sericite schist, pyritic quartz schist, the massive sulfide horizon, and a quartz (chert) capping. This succession is overlain by less altered rocks of the upper Spud Mountain tuff, composed of meta-andesite, phyllite, pebbly sandstone or tuff, and a "gritty" sericite schist zone. This, in turn, is overlain toward the east by Iron King andesite, which exhibits pillow lava textures.

The ore zone is composed of multiple en echelon massive sulfide lenses that lie on the topmost surface of the lower Spud Mountain tuff and are intermittently overlain by a chert cap (which the miners called quartz). The structure of the ore horizon is complex in detail and is probably shear folded and faulted into individual ore shoots that rake nearly due north at about 45-60°, as shown in figure 9. The metarhyolites in the footwall are at

least 350 feet thick and show pervasive sericite alteration. The footwall beds 120-150 feet immediately below the ore horizon also contain disseminated pyrite.

Gilmour and Still (1968) also described an interesting copper zone located 150-200 feet stratigraphically below the main zinc-lead ore horizon. The zone is contained within quartz-sericite schist of the lower Spud Mountain tuff. Attempts to mine the copper ore were abandoned in 1961 because of mining problems and the lack of a copper milling circuit. The ore assay grade was 2.36 percent copper, 4.32 percent zinc, 0.05 percent lead, 0.029 oz/t gold, and 0.67 oz/t silver over an average stope width of 4.65 feet. The shape of the six known copper oreshoots rarely exceeds a strike length of 250 feet, but one extends down a 75° plunge for over 2,500 feet. It is doubtful if this lower copper horizon has as yet been fully explored.

Lawrence and Dixon (1986) believed that the copper horizon is also volcanogenic. It attests to the existence of "stacked" ore systems at the Iron King area, with successive horizons exhibiting different sulfide and alteration assemblages. They described recent detailed surface mapping and geochemical surveys over the ore zones and concluded that the Spud Mountain tuff originated as crystal-rich tuffaceous sediments of alternating mafic and felsic composition. The "upper 200 feet are marked by multiple sulfide-bearing siliceous exhalite horizons, which generally increase from a fraction of an inch to 14 feet at the top of the unit" (Lawrence and Dixon, 1986, p. 371). They further stated that "outcrop patterns also suggest that isoclinal folding and transposition of bedding has taken place." Soil geochemical traverses, run normal to the strike, reveal copper highs that are displaced about 200 feet west-northwest from the high lead and zinc values situated directly over the main ore horizon.

Old Dick District, Bagdad Area, Yavapai County

The ores produced from the region surrounding the town of Bagdad contain a variety of different orebodies ranging from Early Proterozoic to Laramide. Keith and others (1983) assigned the large Laramide copper-molybdenum porphyry deposit (Bagdad Copper) to the Eureka district, which also includes the nearby Hillside Au-Ag-Zn-Pb vein deposit (not to be confused with the Hillside district west of Prescott). Several Zn-Cu massive sulfide orebodies of Early Proterozoic age were assigned to the Old Dick district. A nearby Precambrian wolframite vein is assigned to the Tungstonia district.

All mineralization, except for the tungsten deposit, was originally thought to be Laramide by Anderson and others (1955) based on earlier field work. The massive sulfide deposits were believed to have been replacement bodies. Baker and Clayton (1968) held a similar view toward the replacement model. Anderson (1968) revised his earlier view and concluded that the massive sulfide deposits of the Bagdad area were Precambrian. A galena sample from the Old Dick mine revealed a lead isotope age of 1700 Ma

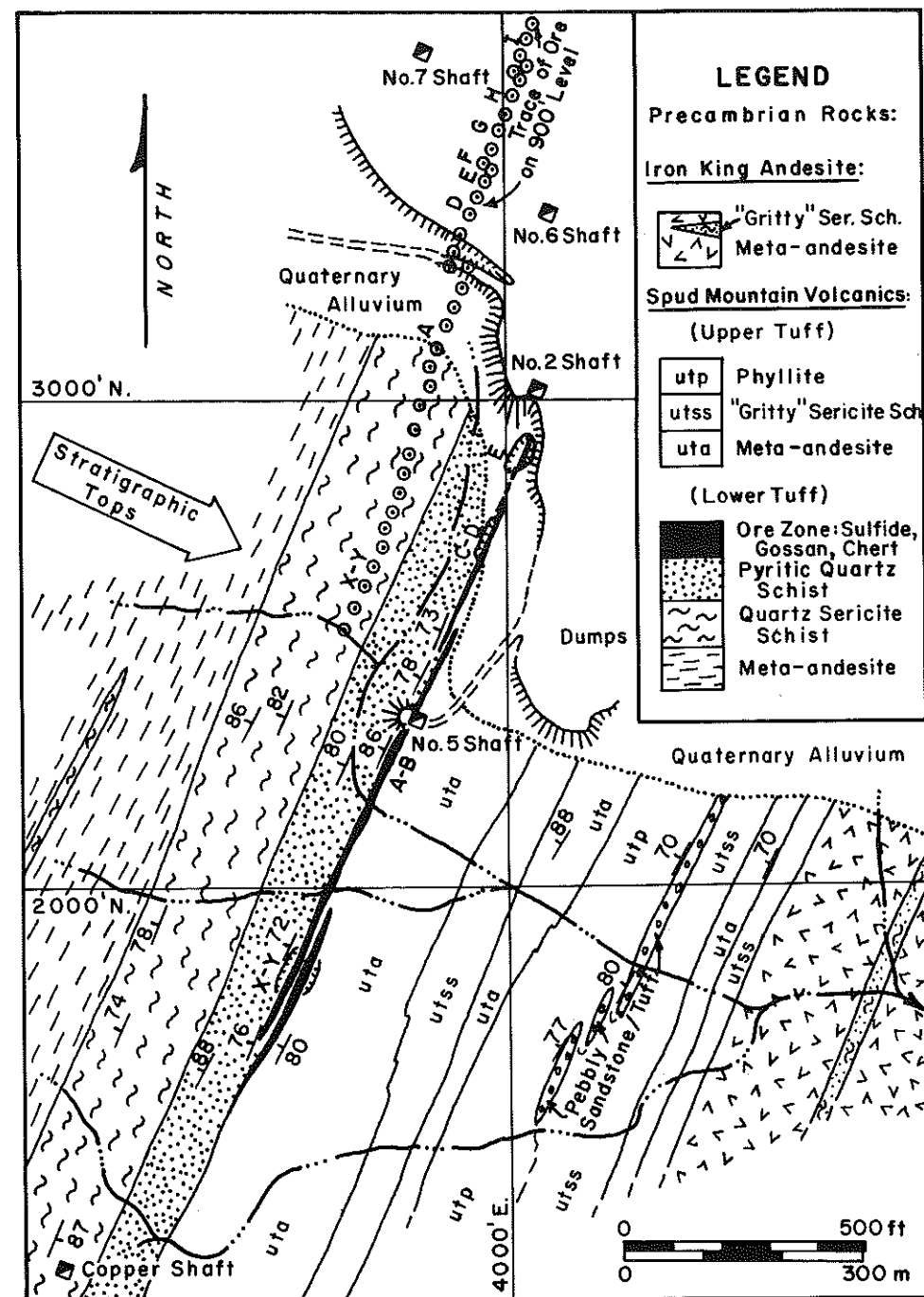


Figure 8. Geologic plan map of the surface outcropping of the Iron King deposit, Humboldt, Arizona. The individual ore lenses are lettered and can be seen at their surface locations and their plunge positions on the 900-ft mine level. The ore horizon is steeply overturned. Refer to the longitudinal cross section (fig. 9) for areas of stoping. (Modified from Gilmour and Still, 1968).

(Doe, 1966, cited by Anderson, 1968, p. 1172). Later, Clayton and Baker (1973) obtained a lead isotope age of 1740 Ma from a Bruce mine galena sample.

The Old Dick district was the third largest producer of Proterozoic massive sulfide ores in the state. The mines contributed an estimated 3.7 percent of the tonnage, 30.4 percent of the zinc, 3.1 percent of the copper, 1.1 percent of the lead, 0.9 percent of the silver and 0.2 percent of the gold from this ore type (tables 1 and 3). The Bruce orebody

was the largest and last found. As the Old Dick deposit was nearing exhaustion, exploratory drilling below and to one side discovered the blind companion orebody. The Copper Queen and Copper King were similar but smaller deposits that also produced high-grade ore. Small production also came from the Pinafore, Red Cloud, Rudkins, and Queen Bee deposits. The mines, now inactive, produced approximately 1.7 million short tons of ore grading 12 percent zinc and 3.47 percent copper.

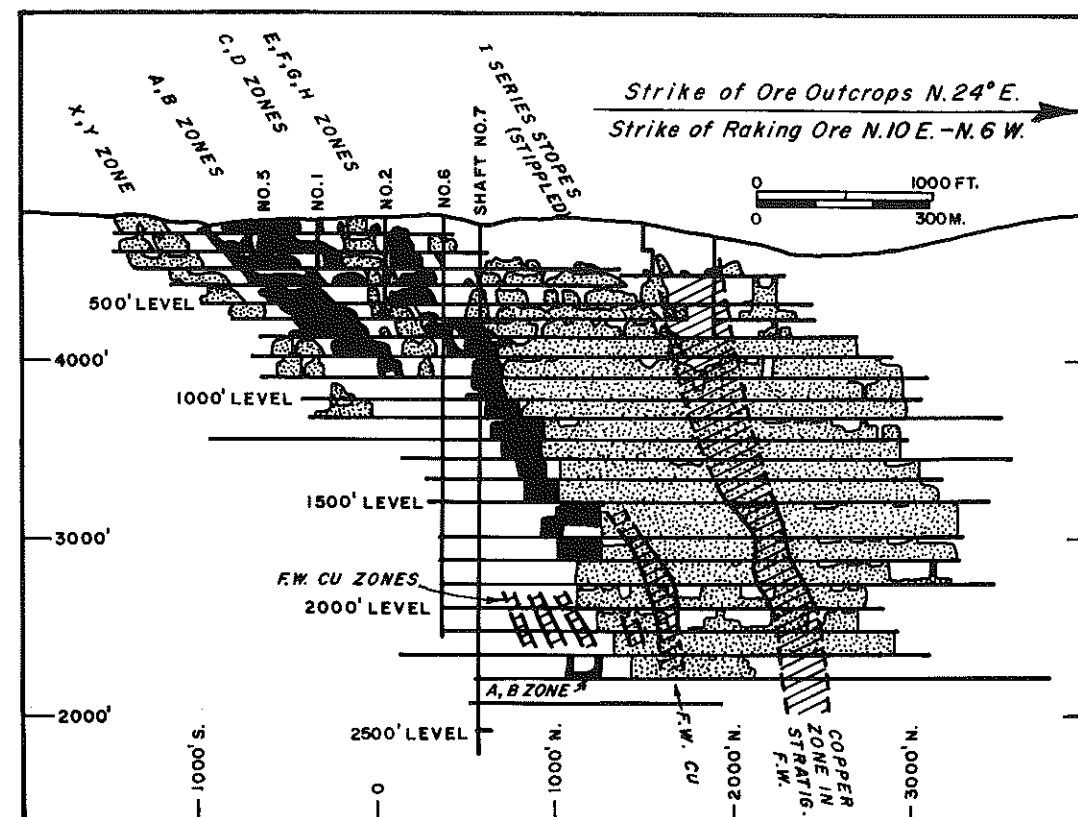


Figure 9. Composite longitudinal section through the Iron King mine workings, facing west-northwest. The stoped areas are shown by alternating stippled and solid color. Disruptions in ore zones probably result from shear faulting of the stratiform sulfide body at north-plunging chevron fold crests. There are at least six known copper zones, but these lie 150-200 ft into the footwall (behind section) and clearly mark an older mineralization event than the one that produced the main zinc-lead orebody. Note that, although the overall outcrop strike of rock and gossans is N. 24° E., the average rake of the oreshoots is due north. This section has been redrawn and reoriented from Gilmour and Still (1968, figs. 2 and 9, p. 1243 and 1250).

Figure 10 shows the general geology of the Old Dick district based on compilations and new mapping by Conway and others (1986). Precambrian Hillside mica schist (Anderson and others, 1955) and the Laramide porphyry stock lie a short distance to the northeast of the Old Dick massive sulfide district, on the eastern side of the Mountain Spring fault. Because all known massive sulfide deposits lie on the western side of the fault, only that part of the Proterozoic stratigraphy will be discussed further.

The most recent synopsis of the volcanic stratigraphy of the Old Dick district was presented by Conway and others (1986) and Conway (1986). Their work builds on the framework established by earlier workers (Anderson and others (1955), Baker and Clayton (1968), Cavalero (1976), Larson (1976, 1984), Collins (1977), and Connelly and Conway (1983)). The oldest unit in the area is the Bridle formation, which is composed of basaltic flows, pillow lavas, coarse mafic clastics, mafic "agglomerate" and tuff, and minor felsic volcanoclastic rocks. The stratigraphic base of the Bridle formation is not seen, but a layered gabbro-anorthosite intrusive rock is believed to occupy that portion. In the vicinity of the outcropping gossans of the Old Dick deposit, the Bridle formation strikes northeasterly and is overturned with steep dips toward the

northwest. The Old Dick and Bruce massive sulfide orebodies are located at the top of the Bridle formation and are intimately associated with a thin horizon of quartz-sericite schist.

Larson (1976, 1984) studied the Bruce orebody and geochemistry of the alteration pipe while the mine workings were still accessible. He documented a large chlorite-sericite alteration zone extending northwest for several hundred feet into the andesite footwall. The location of the Bruce alteration pipe is shown in figure 11A, and a schematic palinspastic section is presented in figure 11B.

The Bruce orebody is an oval lens that is approximately 600 by 1,500 feet with its long axis raking 70° SW. The body reaches a thickness of about 30 feet directly over the alteration zone. Patches of strong alteration, however, extend above the ore into the postore Dick Rhyolite hanging wall. The Bruce deposit is composed of approximately 90 percent sulfide, with pyrite as the chief gangue mineral. Chalcopyrite, sphalerite, and galena are the principal ore minerals with minor amounts of associated arsenopyrite, pyrrhotite, cubanite, and mackinawite.

Conformably overlying the Old Dick and Bruce ore horizon is the Dick Rhyolite. Cavalero (1976) believed that the feeder zone for the extensive flow complex lies about

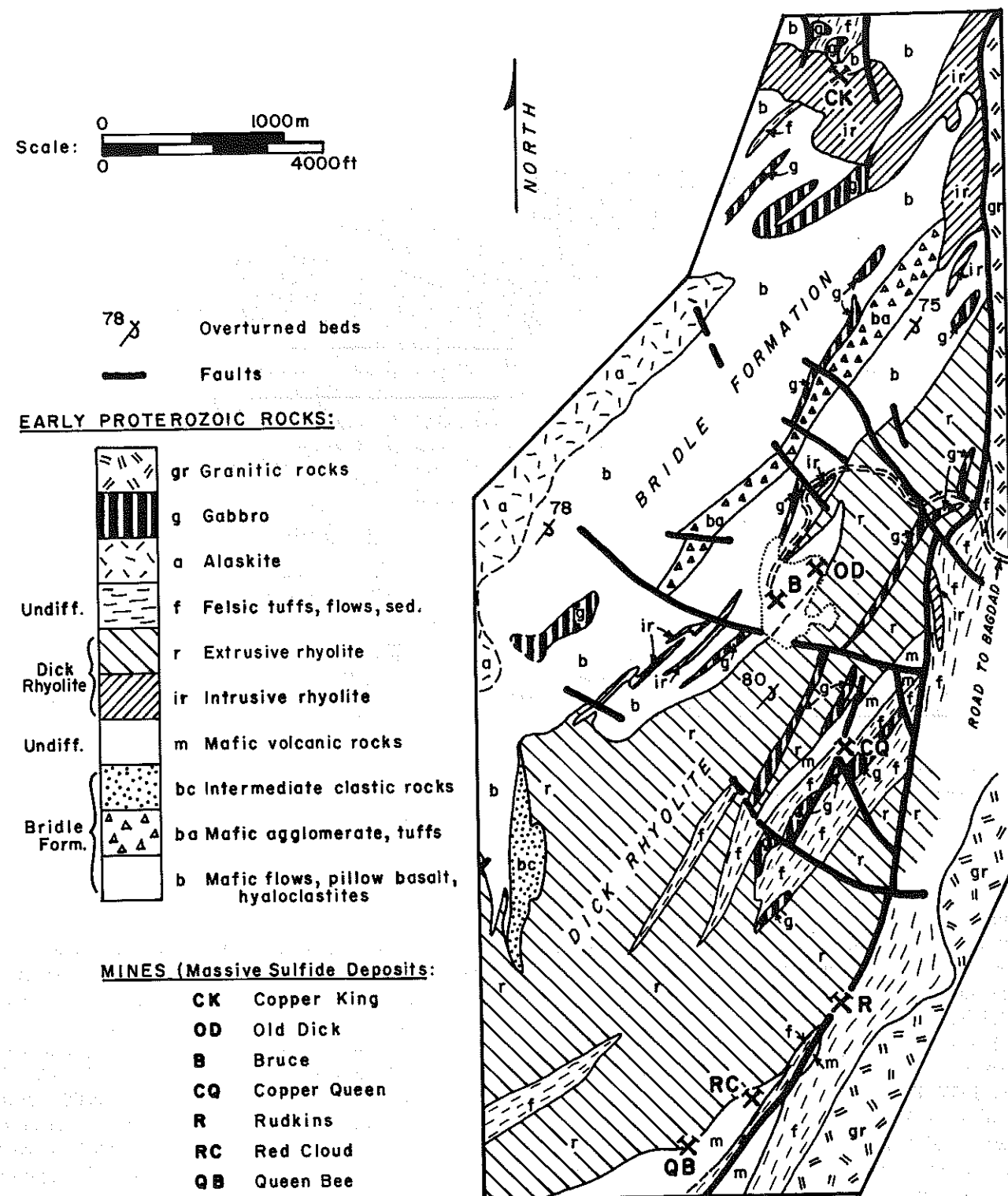


Figure 10. Lithostratigraphic map of the Old Dick district, Bagdad, Arizona (modified from fig. 2 of Conway, Connelly, and Robison, 1986).

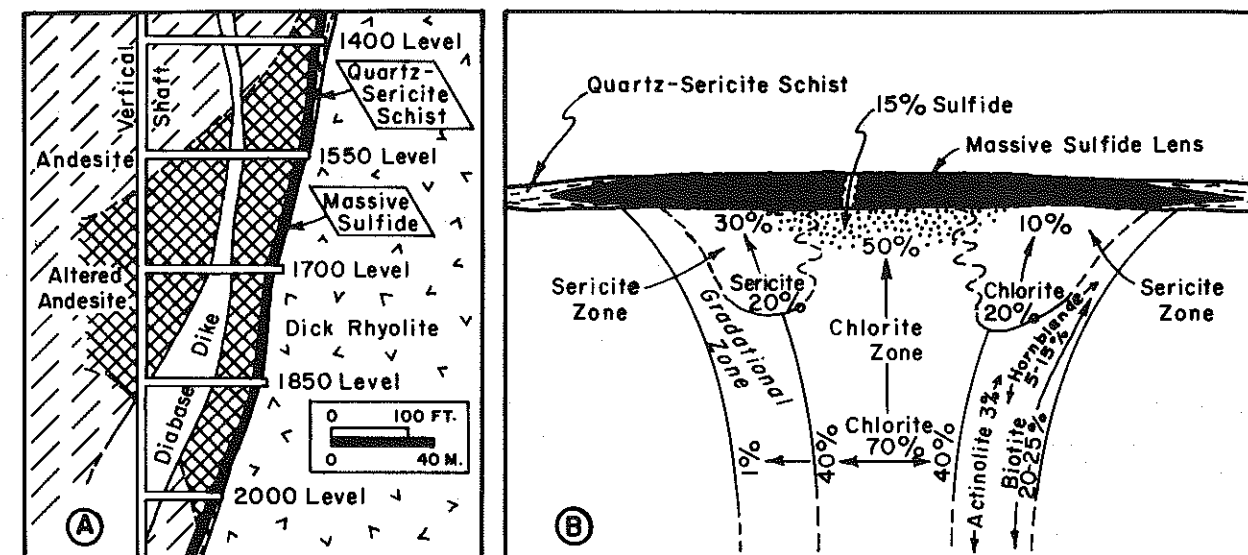


Figure 11. Real and reconstructed cross sections through the Bruce orebody, Bagdad, Arizona. A: Cross section through overturned Bruce mine orebody and alteration zone, facing northeast. The geology has been projected to a vertical plane that trends N. 55° W. and passes through the shaft. B: Schematic palinspastic section showing the distribution of alteration and metamorphic phases in the Bruce orebody alteration pipe, based on concentrations in weight percent. Redrawn from Larson (1984, fig. 2, p. 1882 and fig. 5, p. 1891).

2 miles southwest of the mines. Conway and others (1986) regarded the Dick Rhyolite as a thick (7,000+ feet), southeast-facing composite volcanic pile which inter-tongues with andesite flows, felsic tuffs, and sediments on its flanks. The Copper Queen massive sulfide deposit lies on the southeast side of the Dick Rhyolite contact and is also presumed to face southeast. However, Baker and Clayton (1968, p. 1313) remarked on the similarity of ores and host lithologies at the Old Dick and Copper Queen mines. They stated that the "Queen orebody is 100 feet from the southeastern edge of the [Dick] rhyolite, wholly within a 150-foot band of quartz-sericite schist" and "The [Old] Dick ores are in inter-bedded quartz-sericite schist and andesite at the northwestern contact of the [Dick] rhyolite." The remarkable similarity of geologic setting, tenor of ores, and lack of a chlorite alteration zone at the Copper Queen deposit in the presumed Dick Rhyolite footwall lead me to conclude that an intervening synclinorium is permissible between the two deposits.

Directly southeast of the Copper Queen mine are andesite (or dacite) flows, felsic tuffs and bedded sediments. The bedded units display pronounced isoclinal folding (Cavalero, 1974, 1987, personal commun.). Furthermore, the host rocks at the Red Cloud mine appear to be a repetition of the Copper Queen stratigraphy, which suggests duplication by folding.

Mayer District, Blue Bell and DeSoto Mines, Yavapai County

Following the usage of Welty and others (1985) and the production figures of Keith and others (1983), the Mayer district includes only the Blue Bell and DeSoto mines. The reported 1.4 million tons is assumed to have all come from

the Blue Bell mine, because no tonnage was given for the DeSoto mine. Lindgren (1926) reported that the DeSoto mine yielded at least 180,000 tons of ore that averaged about 3.75 percent copper, 0.02 oz/t gold, and 1 oz/t silver.

The Mayer district ranks fourth in total production of massive sulfide tonnage in the state. The district produced at least 3 percent of the tonnage, 2.4 percent of the copper, 3 percent of the gold, and 2.2 percent of the silver produced from this ore type. The Blue Bell mine is situated 4 miles south of Mayer and according to Anderson (1972) the mine produced ore from 1896 to 1926, and again from 1944 to 1948. Lindgren (1926, p. 145) noted that the Blue Bell "ore is classified as heavy smelting ore and siliceous concentrating ore and averages 3 per cent in copper. The smelting ore contains also 1.5 ounces of silver and 0.05 ounces of gold to the ton." The complex orebody is composed of six lenses, up to 40 feet wide, that plunge from vertical to 75° S. Sericitized and chloritized "quartz porphyry" is suspected to be the volcanic host to the orebody.

Hualapai District, Mohave County

The Hualapai district is located approximately 20 miles south-southeast of Kingman, in the west-central Hualapai Mountains, and 45 miles northwest of the Old Dick district at Bagdad. Two small massive sulfide deposits, the Antler and Copper World, reportedly produced 161,000 tons of ore from 1918 to 1970 (Keith and others, 1983). Figure 12 shows the location of the mines and the general geology of the area.

Stensrud and More (1980) presented a convincing summary of the geology of the district. Amphibolite-grade metamorphism has converted protoliths of rhyodacitic to

rhyolitic tuffs and tuffaceous sediments into quartzfeldspathic and quartz-mica gneiss, schist, and phyllite. Protoliths of basaltic to andesitic flows and thin tabular intrusive bodies have been converted into amphibolite by regional metamorphism. Kessler (1976) reported a $^{87}\text{Rb}/^{87}\text{Sr}$ date of 1800 (± 470) Ma for a granodiorite gneiss that lies to the north of the Hualapai rock suite and may be time equivalent.

The sulfide bodies have been recrystallized and plastically deformed and, unlike the massive sulfide ores at Jerome and Bagdad, the Hualapai deposits contain substantial pyrrhotite. Furthermore, the former Mg-rich chlorite alteration zone in the footwall has been converted into an assemblage of cordierite, anthophyllite, almandine garnet, magnetite, and biotite with a distinct bladed texture. Similar products of thermal metamorphism have been described in the Rouyn-Noranda district in Quebec (De Rosen-Spence, 1969). The rock suite has been intruded by numerous semiconformable, elongate Precambrian plutons and by later Precambrian pegmatites and diabases.

The Antler mine produced 78,000 tons of ore with an average grade of 3 percent copper, 6.5 percent zinc, 0.01 oz/t gold, and 1.1 oz/t silver from the time of its discovery in 1879 to the last production in 1970 (Still, 1974). The orebody strikes northeast and dips northwest, and the ore

plunges 63° N. Primary minerals below the level of oxidation are pyrrhotite, sphalerite, chalcopyrite, pyrite (with intergrown magnetite), and galena. The sulfide mineralization extends for over 2,000 feet along strike and ranges from 2 to 40 feet in width.

The Copper World mine produced at least 16,000 tons of ore grading 3.55 percent copper, 10.29 percent zinc, 0.0017 oz/t gold, and 0.66 oz/t silver from 1944 to 1959 (Forrester, 1963). Additional ore was mined in 1970. Sulfide mineralogy and metamorphic effects for the Copper World deposit (Stensrud and More, 1980) are almost identical with those at the Antler except that the pyrite far exceeds pyrrhotite in abundance. Amphibolites are lacking in the vicinity of the Copper World mine.

Important iron formations are closely associated with the Antler orebody as well as occurring at a distance from the known ore. Several lenses of iron formation, associated with metamorphic fibrous silicate masses (former Mg-chlorite alteration), are found at the "Bulge," north-northeast of the Antler deposit, where an amphibolite layer thickens substantially and makes a conspicuous bulge in the outcrop pattern. Stensrud and More (1980) favored a northwest-younging stratigraphic succession at this location and implied that the "Bulge" is a site favorable for massive sulfide exploration.

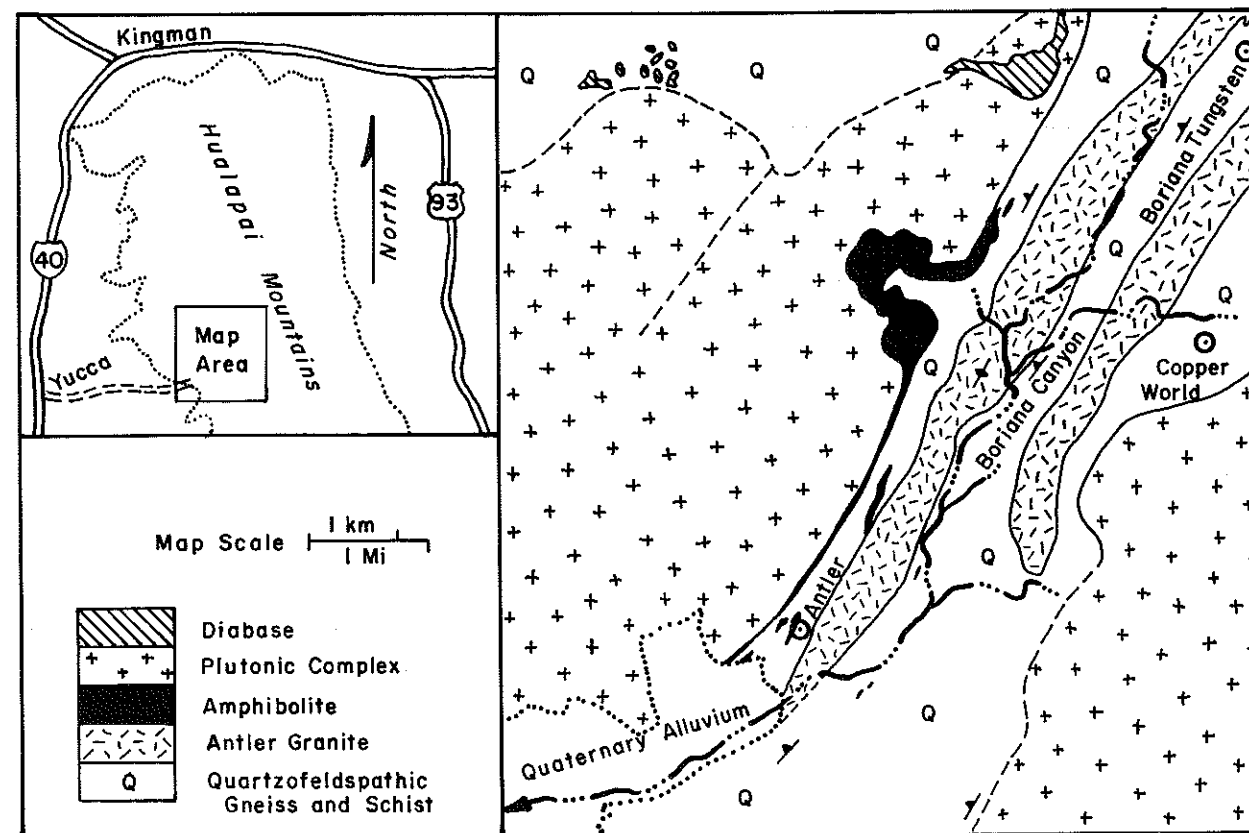


Figure 12. Regional geologic setting of the Antler and Copper World massive sulfide deposits, Hualapai district, Mohave County, Arizona. The conspicuous outcrop pattern in the amphibolite unit is known as the "Bulge." In the northeast corner of the map is the Tertiary Boriana tungsten deposit. The map is redrawn from Stensrud and More (1980, figs. 1 and 2, p. 156 and 157).

Agua Fria District, Yavapai County

The Agua Fria district is reported to have produced 160,000 short tons of massive sulfide ore from 1901 to 1969 (Keith and others, 1983). This would make it the sixth largest producer in Arizona for this ore type. It accounted for approximately 0.34 percent of the tonnage and 0.3 percent of the copper, with minor production of zinc, gold, and silver. The larger deposits in the district include the Binghampton, Copper Queen, and Stoddard, plus many smaller prospects. The Copper Queen mine is located about 4½ miles northeast of Mayer and has recently been described by Higgins (1986). The Copper Queen deposit and the nearby Binghampton deposit lie on the sericitized and locally chloritic contact of a quartz crystal tuff or ash flow similar in appearance to the Cleopatra formation at Jerome. Despite the relatively small size of the known Agua Fria deposits, they bear a strong resemblance to the "Jerome type" of massive sulfide ores. Both camps show copper-rich and zinc-poor ores, hosted on large flow complexes. This district should have good exploration potential.

Other Massive Sulfide Districts

In the extreme northern portion of Maricopa County there are three small massive-sulfide-producing districts or prospects. The largest is the Orizaba deposit in the New River district, which is reported to have produced 34,000 tons of copper ore (Keith and others, 1983). The small Bronco Creek and Gray's Gulch districts lie a short distance to the east. The Kay district, in southern Yavapai County, produced small tonnages of massive sulfide ore with good copper grades and small amounts of lead, gold, and silver. Two other areas of massive sulfide prospects are known as the Pittsburgh-Tonto and Pranty's Cabin districts in Gila County. The mineral production from these districts is listed in table 1.

GOLD VEINS (\pm COPPER, \pm LEAD, \pm SILVER)

Following the usage established by Keith and others (1983), the gold-bearing ore deposits described in this section are classified as "veins," although this description may also include stratiform volcanogenic mineralization. Even if metal-bearing source beds are involved, many of these deposits have apparently been subjected to some degree of hydrothermal activity that postdates the original deposition. Economic ore grades may require this additional step.

When past production and future ore reserves are taken into account, one of the largest gold-silver vein systems would appear to be the deposits of the Ticonderoga district. The district is located southwest of the Iron King mine and includes several formerly producing mines. The most recent activity has centered on the McCabe-Gladstone vein with announced reserves of about 500,000 tons of ore grading 0.41 oz/t gold and 2.6 oz/t silver (Stan

West Mining Corporation Annual Report, 1983). A typical mineralized structure is described as containing a central zone (0.5-1 foot) of massive sulfide containing pyrite, chalcopyrite, sphalerite, and galena with a gangue of quartz-calcite-barite. On each side of the steeply dipping massive sulfide core is a zone of quartz-carbonate breccia that contains 1-5 percent sulfides and is about a foot thick. On either side of the breccia zones is pyritic andesite, whereas farther out, the wall-rock andesite is barren of economic values. The sulfide-bearing portion of the vein is believed to carry gold and silver, with an average mining width of 4.9 feet used in the reserve figure.

The McCabe-Gladstone vein system trends approximately N. 60° E. and dips about 76° SE. The southwestern extension of the vein is called the Little Kicker-Rebel system. A parallel vein to the southeast of the McCabe is called the Adventure system. A discordant north-trending vein, called the Henrietta system, intersects the main mineralization between the McCabe and Gladstone shafts. Other mines in the area include the Silver Belt, Arizona National, Lookout, and Kit Carson.

From 1867 to 1979 the Ticonderoga district produced 336,000 tons of ore, which had a yield of 2,593,000 pounds of copper, 3,217,000 pounds of lead, 29,000 pounds of zinc, 189,000 ounces of gold, and 1,575,000 ounces of silver (Keith and others, 1983). The Richinbar district in Yavapai County was reported to have produced 32,000 tons of similar ore from 1905 to 1971, and even produced small amounts of tungsten. The third-ranking district appears to be Cottonwood in Mohave County, where 13,500 tons of ore were mined from 1907 to 1968. Good copper values were encountered, and a small amount of tungsten was produced in addition to the precious-metal values. Other deposits in this category are shown in the list that accompanies figure 1.

COPPER LODES AND VEINS (\pm GOLD, \pm LEAD)

A series of small copper deposits occurs from Pinal to Mohave Counties (fig. 1). Production from individual mines and prospects ranges from 100 to 7,800 tons, with copper as the chief commodity and with variable amounts of precious metals (Keith and others, 1983).

TUNGSTEN DEPOSITS

The ages of tungsten deposits in Arizona are often difficult to define. A number of deposits are hosted in Precambrian rocks but are not necessarily of that age. A good discussion of tungsten deposits was given by Hobbs (1969). In the following discussion the deposits of Precambrian age are taken from the listing by Keith and others (1983).

Figure 13 shows the distribution of tungsten deposits that are interpreted to be mainly of Middle Proterozoic age. One of the largest producers was the Camp Wood district, located approximately 33 miles west-northwest of

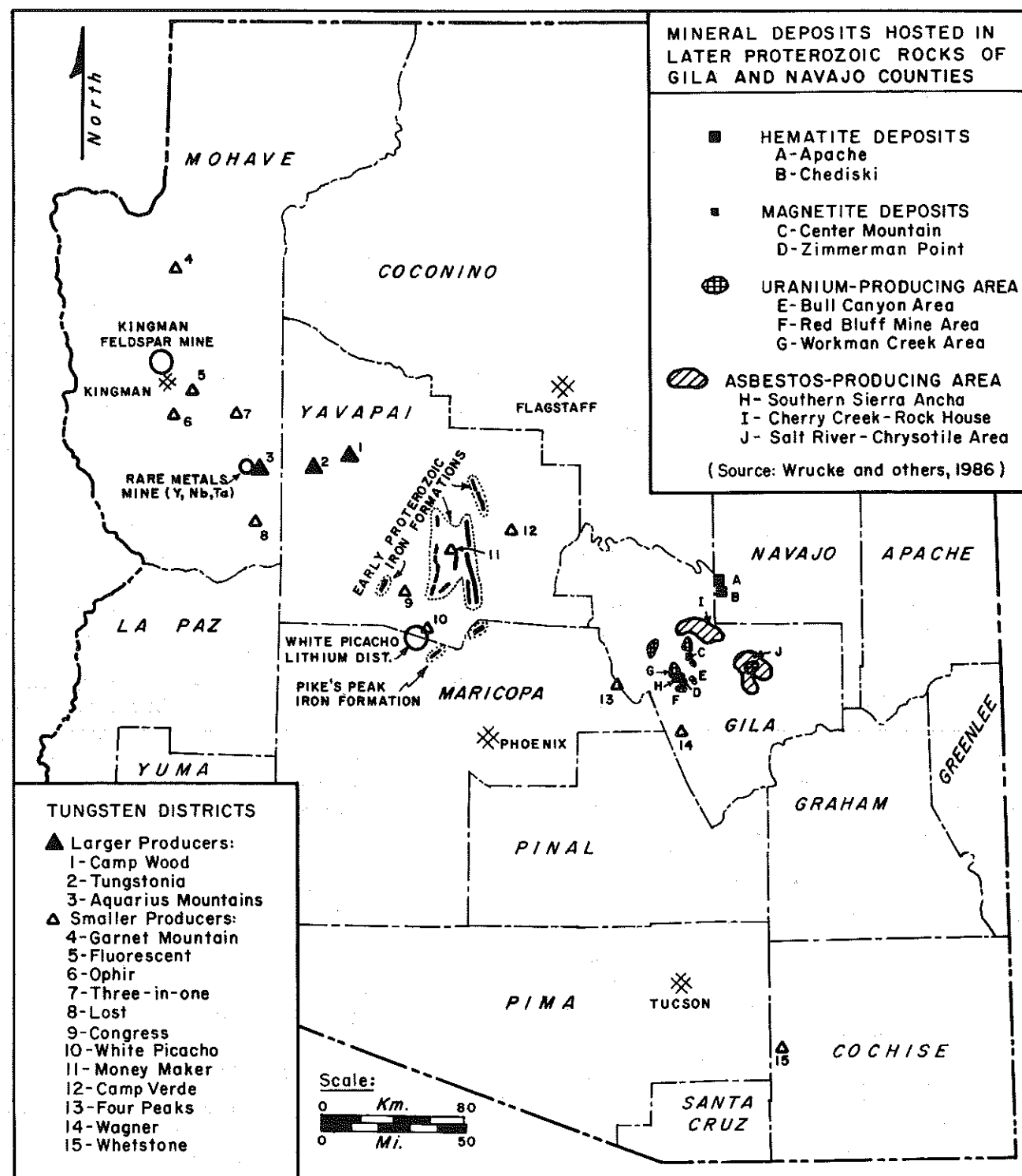


Figure 13. Arizona location map showing Precambrian tungsten districts, major pegmatite areas (feldspar, rare-earth minerals, lithium), Early Proterozoic taconite iron formations, and Late Proterozoic iron-, uranium-, and asbestos-producing districts.

Prescott. Production is reported to have been 8,686 short ton units of WO_3 (a short ton unit, or stu, is equal to 1 percent per ton or 20 pounds). The second largest producer was the Tungstonia district, also in Yavapai County. The deposit lies to the northeast of Bagdad and produced more than 7,500 stu WO_3 . Anderson and others (1955) reported that the chief ore mineral in the east-trending vein was wolframite, but that some disseminated scheelite was also found in siliceous pyritic wall rock between wolframite-bearing veins. The deposit also contains a small amount of beryl.

The third largest reported producer was the Aquarius Mountains district of Mohave County. In addition to the 3,327 stu WO_3 produced, small amounts of manganese ore were mined as well from 1969 to 1973. Most of the tungsten ores occur within quartz veins or as irregular replacements in igneous or metamorphic host rocks. The Boriania deposit is located in the northeastern part of the Hualapai massive sulfide district (fig. 12) and is regarded as Tertiary, despite the fact that the host igneous and metamorphic rocks are probably Precambrian. Hobbs (1969) reported that only when veins cut overlying Tertiary strata can one be fully sure of the age. The Boriania deposit was the state's largest producer and from 1919 to 1957 provided more tungsten ore than all other deposits of all ages in the state combined.

URANIUM DEPOSITS

Although there are many uranium deposits scattered throughout Arizona, few can be classified as Precambrian. Wrucke and others (1986) described the Middle Proterozoic deposits that are located in the southern Sierra Ancha area of Gila County. The principal host rock for the ore is a hydrocarbon-bearing siltstone member of the Dripping Spring Quartzite within the Apache Group. Uranium is believed to have been initially leached from an associated air-fall tuff and concentrated in anomalous amounts within the black, carbonaceous, pyritic siltstone. From this protore, ores were later formed in subvertical veins and in adjacent sedimentary rocks along zones within north-trending monoclines. Subsequent diabase sill and dike intrusion is thought to have aided ore deposition.

The uranium-producing areas are shown in figure 13. Ore was first discovered at the Red Bluff mine in 1950. From 1953 to 1969 fourteen mines shipped 21,851 tons of ore that averaged 0.24 percent U_3O_8 (Otton and others, 1981). Additional exploration in the late 1970s led to the discovery of more ore reserves. An ore deposit near Workman Creek is reported to contain 8.8 million pounds of U_3O_8 at a grade of 0.11 percent (Nutt, 1984).

IRON DEPOSITS

There are basically two forms of iron deposits in the Precambrian rocks of Arizona. Although not used as a source of iron ore, the Early Proterozoic sedimentary

banded iron formations of central Arizona may constitute a resource for future generations. These conspicuous linear "marker horizons" (see fig. 13) emphasize the overall north-south structural grain of a broad belt of Yavapai Series rocks that bracket the Kay district and Shylock Zone. The Pike's Peak iron formation in northern Maricopa County, described by Slatt and others (1978), crops out along strike for over 2½ miles. It is situated at the end of a discontinuous belt that stretches northward for over 50 miles before being lost beneath Phanerozoic cover rocks on Mingus Mountain, just west of Jerome. The Pike's Peak deposit is composed of numerous subparallel lenses of banded cherty iron formation contained within a complex unit that includes phyllite, rhyolite, and diorite. The steep beds strike N. 60° E. Preliminary reserve estimates indicate that 100 million short tons of taconite containing 31 percent iron are available to a mining depth of 425 feet. The formation can be compared with the classic hematitic iron formations (taconites) found in the Lake Superior region.

A completely different type of iron deposit is found in Middle Proterozoic sedimentary and volcanic rocks in the southwestern corner of Navajo County and the adjacent Sierra Ancha area of Gila County. According to Wrucke and others (1986) and references cited by them, beds of hematite were formed during lateritic weathering of basalt flows in the Mescal Limestone. Hematite was concentrated in karst breccias and is quite extensive in the Apache iron district of Navajo County. The largest deposit is the Apache which contains a hematite-rich zone that varies from 20 to 70 feet in thickness and can be traced for nearly 2 miles along strike (Shride, 1967). The Chediski deposit lies a short distance to the south, has a thickness of just over 20 feet, and is continuous for nearly 2 miles (Harrer, 1964). The hematite ores vary from soft and earthy to hard and dense.

At Zimmerman Point in the Sierra Ancha area of Gila County, some of the hematite beds have been partially converted to magnetite by subsequent diabase sill and dike intrusions. One such bed of magnetite, up to 100 feet thick, contains an estimated 16 million tons of ore with a grade range of 20.0-67.9 percent iron (Otton and others, 1981).

ASBESTOS DEPOSITS

Wrucke and others (1986) reported that there were three areas of sporadic chrysotile asbestos production from Gila County from 1914 to 1982. The three areas are shown in figure 13. An estimated 160 small deposits contributed nearly all of Arizona's total production of 75,000 tons of asbestos fiber through 1966. Mining was done in the Salt River-Chrysotile, Cherry Creek-Rock House, and southern Sierra Ancha areas of Gila County. Some ores produced long-staple fiber (spinning grade), whereas others produced short-fiber asbestos for other commercial applications.

Thin, tabular bodies of calcium magnesium silicate minerals were formed when diabase cut across karst horizons within the Mescal Limestone. Metamorphic reactions between cherts deposited within the karst horizon and dolomitic host rock formed the asbestos veins. Individual asbestos veins may exceed 2 inches in width and may be contained within a serpentine envelope that is commonly 0.5-1.5 feet thick. Most asbestos deposits are typically located within 25 feet of the upper or lower contact of a diabase sill where it crosscuts stratigraphy.

PEGMATITE DEPOSITS

Important pegmatite deposits occur throughout Arizona, but only a few of the larger ones will be discussed here. The Kingman feldspar mine is located just north of Kingman and has been described by Heinrich (1960). The deposit has produced more than 100,000 tons of crude and ground potash feldspar (microcline) since quarrying began in 1924. The sill-like pegmatite body of Precambrian age strikes northeast and dips steeply northwest. A 40-200-foot-thick core zone contains masses of white microcline up to 12 feet across and pods of gray quartz up to 15 feet long. The border zone is aplitic. The ores contain minor allanite that contains significant amounts of cerium, lanthanum, neodymium, thorium, yttrium, and other rare-earth elements. Heinrich (1960) also reported on the occurrence of rare-earth minerals at the Rare Metals mine in the Aquarius Mountains southeast of Kingman.

An important cluster of pegmatite bodies is found in the White Picacho district, described in detail by Jahns (1952). Figure 13 shows the location of the district, which straddles the boundary between Yavapai and Maricopa Counties. Additional descriptions and a field guide have been presented by London and Burt (1978).

Jahns (1952) described pegmatite bodies at the North Morning Star, Lower Jumbo, White Jumbo, Picacho View, Outpost, Friction, Midnight Owl, and Long Dike mines as well as eight other prospects in the district. The pegmatites of the White Picacho district occur within igneous and metamorphic rocks of Precambrian age along a curving belt that is at least 10 miles long and up to 3 miles wide. The pegmatites show as irregular white bodies set against darker host rocks. The pegmatite bodies include dikes, sills, pods, and irregular branching shapes. Ratios of length to width may vary from 2:1 to 120:1, with maximum lengths of up to 2,000 feet. Most bodies are quite small.

Jahns reported that there are three types of pegmatites in the district. The most abundant type contains mineralogically simple assemblages of quartz, potash feldspar, and subordinate sodic plagioclase and muscovite. Accessory minerals include garnet, biotite, beryl, and black tourmaline. The second type is similar in bulk composition, but contains more varied concentrations of accessory minerals and tends to be more coarsely

crystalline. The third type contains lithium-bearing minerals and is subordinate to the other types. These pegmatites contain quartz, potash feldspar, spodumene, amblygonite and other lithium-bearing phosphate minerals, lepidolite, and pink and green tourmaline.

Production from the White Picacho district, roughly arranged in order of economic value, came from feldspar, amblygonite, spodumene, beryl, bismutite, muscovite, and minor columbite-tantalite. Moderate reserves are present in the district, but international supply and demand will determine future production.

MINERAL EXPLORATION OUTLOOK

Despite the slump in metal prices in the 1980s and the overall slowdown of mineral exploration activities in North America during that time, the outlook for additional future ore discoveries in the Precambrian rocks of Arizona is very good, in my opinion. Although much of the exploration activity of the late 1980s will undoubtedly remain directed at precious-metal deposits, the greatest future mineral potential may lie in the discovery of concealed volcanogenic massive sulfide and associated gold deposits.

Most massive sulfide mining districts throughout the world contain a loosely defined "family" of deposits. Typically the family contains at least one large deposit, several intermediate-sized satellitic bodies, and a host of smaller prospects. The partially exposed Verde district may be typical of part of such a population, with the United Verde orebody as the largest known member. Supergene-enriched massive sulfide deposits of the U.V.X. type are economically attractive targets, especially in the Verde district. Other districts, such as the Big Bug, Agua Fria, and Bagdad, contain orebodies in the small to intermediate size range, and perhaps the "largest member" deposits still await discovery.

Early Proterozoic massive sulfide deposits in Arizona are all directly allied with silicic volcanic rocks that range from very thick and complex, as found in the Verde district, to the thin quartz-sericite schist (formerly a rhyolitic tuff) that is intimately associated with the Old Dick ores. Future exploration in the Old Dick district, for example, should seek a large ore target near the expected source of the silicic volcanism and not in the basaltic Bridle formation. A syncline may exist between the small Old Dick-Bruce and Copper Queen deposits, and drilling into the blind keel of the fold, midway between the known orebodies, would explore a region more favorable for discovering a world-class ore deposit.

Sustained exploration programs, especially utilizing deep pattern drilling, have been highly successful in locating blind orebodies in the Archean Abitibi Belt of the Canadian Shield over the past several decades. Application of similar rigorous techniques in Arizona may locate some large concealed deposits. Depending upon world

conditions, certain strategic minerals may, once again, be looked for in the Precambrian rocks of Arizona. Increased use of rare-earth elements in the electronics industry will certainly expand the already modest exploration activity in the state's alkaline rock suites.

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PROTEROZOIC ANOROGENIC GRANITES OF THE SOUTHWESTERN UNITED STATES

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ABSTRACT

The mountain ranges of Arizona and adjacent California and Nevada contain large areas underlain by Proterozoic anorogenic granites comprising the southwesternmost portion of the 1.4- to 1.5-Ga-old transcontinental belt. Of these, a biotite ± muscovite, monazite-bearing suite resides in central and southeastern Arizona as part of a peraluminous segment that extends through New Mexico into the Colorado Front Range. This group is bordered on the south (southern Arizona to Sonora) and west (Colorado River region) by a marginally peraluminous to metaluminous granitic suite bearing biotite-sphene ± hornblende, fluorite.

All of these 1.4-Ga-aged granites are distinctly more potassic, iron-enriched (relative to Mg), and depleted in Ca, Mg, and Sr in contrast to most older orogenic granitoids that make up much of the host terrane. In general, the large-ion lithophile-element enriched character of these granites is a consequence of limited melting of a water-deficient crustal source at depths greater than 25 to 37 km. For the peraluminous anorogenic suite, this contrast is less extreme, perhaps resulting from a larger degree of melting as a consequence of a greater metasedimentary component and water in its crustal source.

The anorogenic granitic magmas intruded into the upper crust at depths of 8 to 17 km or shallower at temperatures up to 790°C. The most dramatic variation in the crystallization-intensive parameters resides in the oxygen fugacity, which spans three orders of magnitude. Relative to other anorogenic suites, all of the magmas crystallized at elevated levels of fO_2 , as reflected in their assignment to the anorogenic magnetite series. Yet a regionally significant rise in primary fO_2 levels, unmatched elsewhere in the transcontinental belt, occurs for plutons in western Arizona, including the Holy Moses and Hualapai granites. The most extreme case is the Hualapai granite whose biotite Fe-Fe + Mg ratios drop, due to high fO_2 , to a low of 0.27 down from more typical levels of 0.54 to 0.75. Such extreme variations in primary levels of oxygen fugacity must be an indirect imprint of regional changes of the level of oxidation of the lower crust. This area of western Arizona is in proximity to the eastern limit of the 1.4-Ga biotite ± hornblende granites, a boundary that is also approximately equivalent to major changes in the Nd isotopic composition of these granites and the metamorphic and magmatic character of the older orogenic terranes.

On a global scale, the crust-forming orogenies ended by 1.6 Ga and the continents entered a long-lived era dominated by localized extension and transcontinental intrusion of anorogenic potassic rapakivi granite, mafic dike swarms, charnockite, and anorthosite. Perhaps plate consumption became intraoceanic during this time. The profuse and widespread nature of the igneous activity has no Phanerozoic analogue and is considered to be unique to the Proterozoic. A crustal overturn model ties the magmatism to heating within a largely undepleted subcontinental mantle, the eventual rise of mantle plumes, and the transfer of heat into the youthful, undifferentiated Proterozoic crust. Subsequent melting and rise of potassic granitic magmas from the lower crust leads to considerable crustal reorganization, a process that would continue until both the mantle and crust reached a stable configuration.

INTRODUCTION

After 300 million years of orogenesis, the Proterozoic North American craton entered a new era of tectonic quiescence beginning about 1.6 Ga ago. This preceding period of deformation and igneous activity was a time of principal continental growth by episodic crust formation represented by south- to southwestward-younging orogenic terranes, which range in age from 1.82 to 1.90 Ga (Penocean orogeny) and 1.61 to 1.68 Ga (Mazatzal orogeny). The oldest members of these orogenic belts are almost always supracrustal metasedimentary and mafic to felsic metavolcanic rocks intruded by variably foliated granitoid masses, which usually have a calc-alkaline composition. For the next 600 million years, this newly formed Proterozoic crust, unlike

the older Archean, continued to undergo considerable modification involving deep-seated crustal melting, leading to widespread anorogenic intrusion of epizonal, potassium-rich granites into the upper crust. For many areas, the presence of associated mafic intrusions, including large volumes of older gabbro to anorthosite and swarms of diabase, indicates that this thermal disturbance was probably rooted in the mantle. To date, three principal periods of anorogenic igneous activity have been defined: (1) 1.41 to 1.49 Ga, (2) 1.34 to 1.40 Ga, and (3) 1.0 to 1.2 Ga. By far, the first was most profound and constitutes over 60 complexes forming a transcontinental belt (fig. 1) over 1,000 km wide, extending from Labrador to southern California (see J. L. Anderson, 1983, for a more comprehensive review and appropriate references).