The Geology and Ore Deposits of Jerome

Yavapai County, Arizona

Paul Lindberg

Arizona Geological Society Fall Field Trip
November 12-13, 2005

Dear Field Trip Participant,

Welcome to the Arizona Geological Society Fall 2005 field trip to Jerome, Arizona. We sincerely appreciate the time and effort of our trip leader, Paul Lindberg—with more than three decades of experience in the local and regional geology--for leading this trip! We also wish to acknowledge the management of Phelps Dodge Corp. for granting us access to the company property.

Safety is a primary concern for Phelps Dodge and the Arizona Geological Society. Wear your personal protective equipment at all times, and pay attention to your surroundings for your safety and the safety of your fellow participants.

Please enjoy the trip!

Thank you,
David Maher
(VP Field Trips, Arizona Geological Society)

The Volcanogenic Ore Deposits at Jerome, Arizona, A Brief Review of Their Origin and Production History

Paul A. Lindberg, Consulting Geologist, Sedona, Arizona
Arizona Geological Society Field Trip
November 12-13, 2005

In 1585 Hopi guides led Spanish explorers to their source of pigment mining in the gossan outcrop of what was to become the United Verde deposit at Jerome, Arizona. Finding only worthless copper instead of gold, the Spaniards quickly lost interest in the region. Years later, between 1893-1975, the Jerome underground ore deposits ultimately produced more than 3,025,051,000 pounds of copper metal in addition to over 57 million ounces of silver and 1.58 million ounces of gold as byproducts of copper ore refining. Historic mining operations were only focussed on extraction of high-grade copper ore (chalcopyritic). Substantial reserves of sphaleritic zinc ore, copper and gold remain un-mined in the huge pyrite-hosted United Verde deposit.

During the mining life of five Jerome ore bodies, only two of which were exposed in outcrop, the ores were believed to be replacement sulfide deposits sandwiched between a massive intrusive quartz porphyry and a large diorite sill. It was not until the late 1960s that the ore bodies were proven to be classic volcanogenic ore deposits of Early Proterozoic age. A current USGS study, designed to determine the Early Proterozoic oxygen content of the ancient atmosphere, examined the local jaspers associated with the sulfide deposits. As part of this ongoing study a new age date for the time of Jerome ore genesis has been obtained by Sam Bowring (MIT) from zircons extracted from the Upper Cleopatra Rhyolite. The 207Pb/206Pb gave an age of 1738.3 $\pm$ 0.6 Ma. This marks the age for the unaltered rhyolite that immediately caps the Jerome volcanogenic ore bodies.

Of the Jerome area ore deposits, the United Verde (Phelps Dodge) and the United Verde Extension (Verde Exploration) were by far the most important and biggest ore producers. Both of these sulfide deposits were formed on the faulted apex of the extrusive Lower Cleopatra Rhyolite; a gigantic submarine ignimbrite eruption. Caldera faulting of the Lower Cleopatra surface allowed for hydrothermal vents to form large sulfide mounds on the deep sea floor. Rare black smoker columns have been found within the United Verde deposit that are indistinguishable from modern samples dredged from the deep sea floor. Even after erosion of part of the ore deposit, and the mining of 33 million tons of high grade copper ore, the pyrite-hosted United Verde deposit still contains over 100 million tons of massive sulfide. Extraction of underground ore from the United Verde mine became impossible by about 1918 when sulfides within the mine had caught fire. As a result, the United Verde open pit was dug to extinguish the fires.

The separate, supergene-enriched United Verde Extension (UVX) lay hidden beneath Tertiary and Paleozoic cover rocks until its underground discovery in late 1914. Bonanza grade copper ore was mined underground until 1938 when its ores were exhausted. Contrary to popular belief during the first half of the Twentieth Century, the UVX deposit is not the faulted-off apex of the bigger United Verde deposit. It is a separate volcanogenic ore body that lies on the opposite facing limb of the Jerome anticline.

The combination of open pit rocks and adjacent mountainous outcrops provides an excellent three-dimensional look at a classic Precambrian ore system. Underground mining attained a depth of 4500 feet at the United Verde mine. The Jerome area provides one of the best exposed volcanogenic systems anywhere in the world.

In addition to the Precambrian ore deposits, and accessible host rock outcrops, there is an equally fascinating story to be learned from the Phanerozoic cover rocks and the local faulting history. During the Laramide Uplift, approximately 75 million years ago, high-angle reverse faults disrupted the Grand Canyon and Jerome areas. The ancestral phase of the Verde, Bessie, and Valley faults at Jerome and Oak Creek fault near Sedona, all shared the same high angle reverse movement during that event. After the uplift an unusual decollement fault took place below Jerome that was to have a profound effect on the UVX ore deposit. A large mile wide slab of Paleozoic sedimentary rocks slid downhill to the east along the lubricated surface of the Chino Valley shale that lay just above the Cambrian Tapeats Sandstone. The resulting gravity slide created a "pullaway" of strata that directly overlay the buried UVX ore deposit. For the next 60 million years groundwater eroded the overlying rocks and generated a deep channel over the Precambrian ore deposit. Tertiary supergene enrichment of a Precambrian ore body took place and created an ore that had a smelter yield grade of 10.5% copper.

The mines at Jerome are located on the western margin of the Verde graben. The main fault that separates the United Verde and UVX ore deposits by about 1550 feet is the Verde fault. Additional faults along the graben edge drop Precambrian and Phanerozoic rocks by more than 6100 feet toward the core of the rift valley. Because of the subsequent erosion of the graben fault scarps the Jerome ore bodies have been exposed to view.

The tour will endeavor to show the participants an in depth look at a famous mining district and discuss the origin of volcanogenic sulfide ore deposits. The writer has had 34 years of personal work experience in the Jerome district.

Trip Plan

Field trip attendees should arrive in the Cottonwood/Jerome area by Friday evening, **November 11th** for overnight accommodations. Assemble at 9:00 am on Saturday morning, **November 12th** at the northern end of the fence enclosing the United Verde open pit at Jerome, located 1/4 mile north of the Jerome Fire Station off Highway 89A (Perkinsville Road). Car-pooling will be mandatory following that point.

Depending upon weather conditions and group size, the field trip will be given a brief history of the district before examining the exposed rock and ore types found within the United Verde open pit area. Examples of rock and ore types will be shown. A moveable fault model showing the relationship between the United Verde (open pit exposure) and United Verde Extension (underground mine) will be demonstrated.

A prepared lunch will be provided and we will eat at a picnic site at the Jerome State Historic Park. After lunch, geologic and mine models of the Jerome area can be visited in the museum. Before leaving the park a description of the development of the Verde graben will be made. The Verde Valley marks the division between the Colorado Plateau and the Basin and Range physiographic provinces. The quarry operation of the Phoenix Cement plant in the valley will also be described.

On Saturday afternoon the plan is to examine pre- and post ore rock successions to the southwest of Jerome along Highway 89A in Deception Gulch and Hull Canyon. This area contains the Verde Central ore deposit that lies at the base of the Cleopatra Rhyolite, unlike the other deposits of the district that lie at its apex. Explanations of pre-ore rock alteration and unaltered post-ore rock suites will be discussed as well as a synopsis of what is postulated to have been the Early Proterozoic environment in which these ore deposits were associated.

For participants wishing to remain in the Verde Valley overnight, there will be a half-day field trip on Sunday morning, **November 13th**. Meeting time and location will be announced on the previous day, but we will be finished before noon. This session will examine faults associated with the Verde graben that played an important role in exposing the ores of the Jerome district. The toe of a decollement fault below Jerome will be examined as well as seeing the affects of ancestral high angle reverse faulting and much later normal graben faulting. Faults of this type can be found throughout the Verde Valley, Oak Creek Canyon, and Grand Canyon areas.
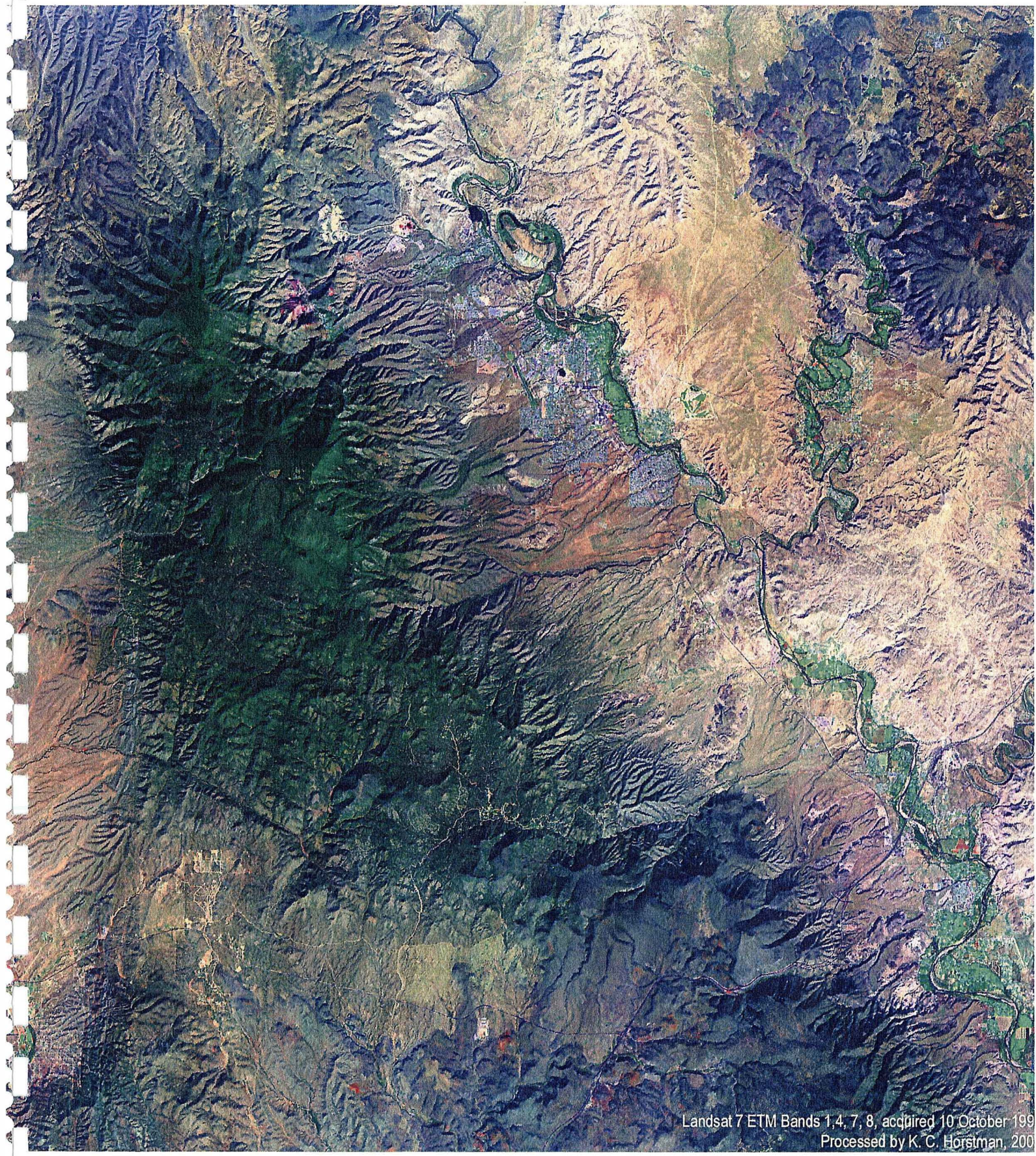
Landsat 7 ETM Bands 1,4, 7, 8, acquired 10 October 199
Processed by K. C. Horstman, 200
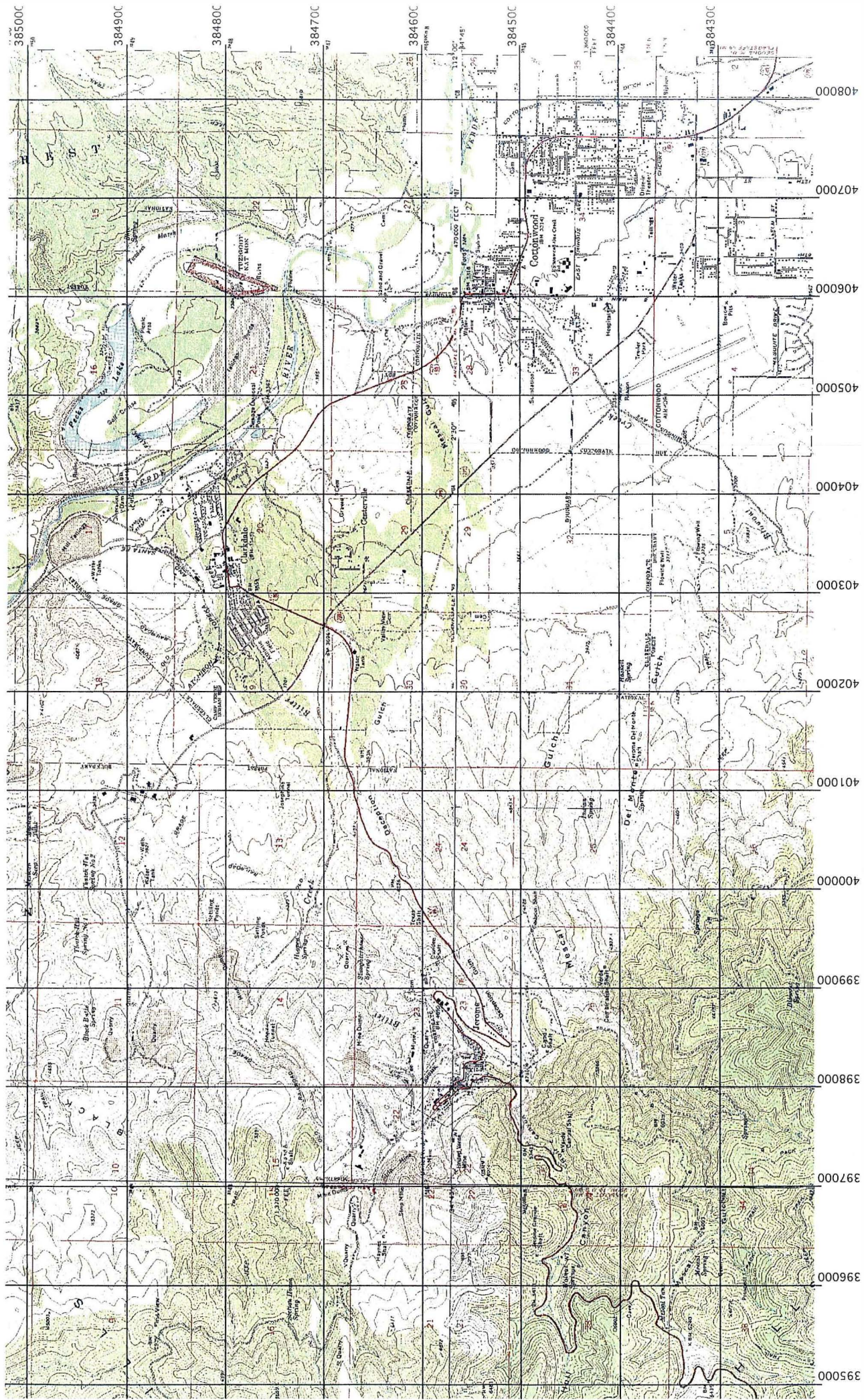
Portions of the Cottonwood, Clarkdale, Hickey Mountain, and Munds Draw Quadrangles

UTM grid NAD 27 projection

1 mile

1 km

in Geologic Diversity of Arizona and its Margins: Excursions to Choice Areas, Davis, G. H., and VandenDolder, E. M., eds.: Arizona Bureau of Mines and Mineral Technology, Geological Survey Branch Special Paper 5, 1987(Field-Trip Guidebook of Geol. Soc. of America, Phoenix, Oct. 26-29, 1987), p. 176-181.

Field-Trip Guide
to the Geology, Structure, and Alteration
of the Jerome, Arizona Ore Deposits

Paul A. Lindberg
205 Paramount Drive
Sedona, Arizona 86336

Mae Sexauer Gustin
Dept. of Geosciences, The University of Arizona
Tucson, Arizona 85721

PURPOSE AND OBJECTIVES

In conjunction with the 100th Annual Meeting of the Geological Society of America at Phoenix in 1987, a one-day, postmeeting field trip (Oct. 30; repeated Oct. 31) will tour a portion of the Verde district and examine the sites of world-class massive sulfide orbodies at Jerome (mines now inactive). Proterozoic stratigraphic successions, evolutionary models for ore formation, and superimposed structural effects will be observed and discussed on site. The trip will leave the Phoenix convention area in the morning and travel by bus to Jerome as shown in Figure 1.

There are two main objectives for this Jerome field trip. First of all, it presents an excellent exposure of a Proterozoic volcanogenic system that produced rich massive sulfide ores of copper, gold, and silver. Two previous G.S.A. field trips to Jerome have been conducted (Lindberg and Jacobson, 1974; Lindberg, 1986a) and scores of geology field classes have toured the district over the past 15 years. Secondly, a newly completed study by Gustin (1986; in prep.) of the redefined Cleopatra Formation adds a new dimension to the understanding of the geological evolution and ore deposit formation of the Verde district. Gustin describes these new data at Stop 5 (see Figure 5) and does not necessarily endorse the interpretation of the cauldron model as proposed by Lindberg (1986a).
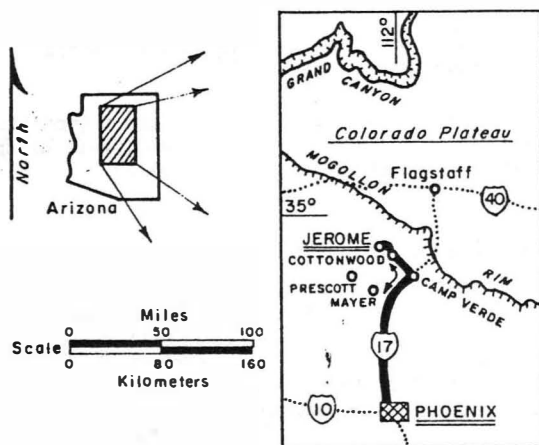

Figure 1. Field-trip route to Jerome, Arizona. Route follows I-17 from Phoenix to Camp Verde, Highway 279 to Cottonwood, and Highway 89A to Jerome. The return to Phoenix is by the same route.

HISTORICAL PERSPECTIVE

In the authoritative study of the Jerome ore deposits, Anderson and Creasey (1958) state that the Spanish explorer "Espejo with four others and Hopi guides visited the copper deposits" on May 5, 1585. They further state that "Farfan arrived at the Jerome deposits on November 24, 1598, and found three estados (16½ feet) deep, and a large dump." It is probable that malachite and azurite pigments were mined from the site in prehistoric times.

Modern mining activities did not commence until about 1883 when small amounts of high-grade oxide ores were mined for gold, silver, and copper. The United Verde deposit became the principal mine in the district. During the early years of mining the easily combustible massive pyrite fed a number of very serious mine fires. This eventually required the excavation of the present United Verde open pit, despite the fact that the overall mining operation was underground. The deposit continued production through two World Wars until its principal copper ores were exhausted in 1953. It produced an estimated 32,784,578 short tons of ore with an average yield of 4.79% copper, 0.043 oz/t gold, and 1.61 oz/t silver. A small lease operation from 1954-1975 mined an additional 206,149 tons of high-grade chalcopyrite vein ore from the footwall that averaged 6.13% copper, 0.014 oz/t gold, and 1.01 oz/t silver.

The bonanza-grade United Verde Extension orebody (U.V.X.) remained concealed beneath Tertiary and Paleozoic rock cover about 3000 feet due east of the United Verde body. The intervening Verde fault offset the section and prevented the U.V.X. from being discovered until 1914. Supergene-enriched ores, mined from 1915-1938, amounted to 3,878,825 tons, which gave an average yield of 10.23% copper, 0.039 oz/t gold, and 1.71 oz/t silver. Supergene enrichment of the Proterozoic ores is thought to have occurred in late Precambrian and again in Tertiary time. The United Verde and U.V.X. ores constituted 99.4% of the Verde district massive sulfide production. The remainder came from oxide and sulfide ores of the Copper Chief (Lindberg, 1986b), Cliff, and Verde Central mines.

GENERAL GEOLOGIC HISTORY

Figure 2 shows the geology of the northern part of the Jerome area, the rock types, and the field-trip stops. Precambrian rock exposures are limited to the immediate west of Jerome by Paleozoic cover, and downfaulted Paleozoic and Tertiary strata further restrict the exposures to the northeast of the Verde fault.

Lindberg and Gustin
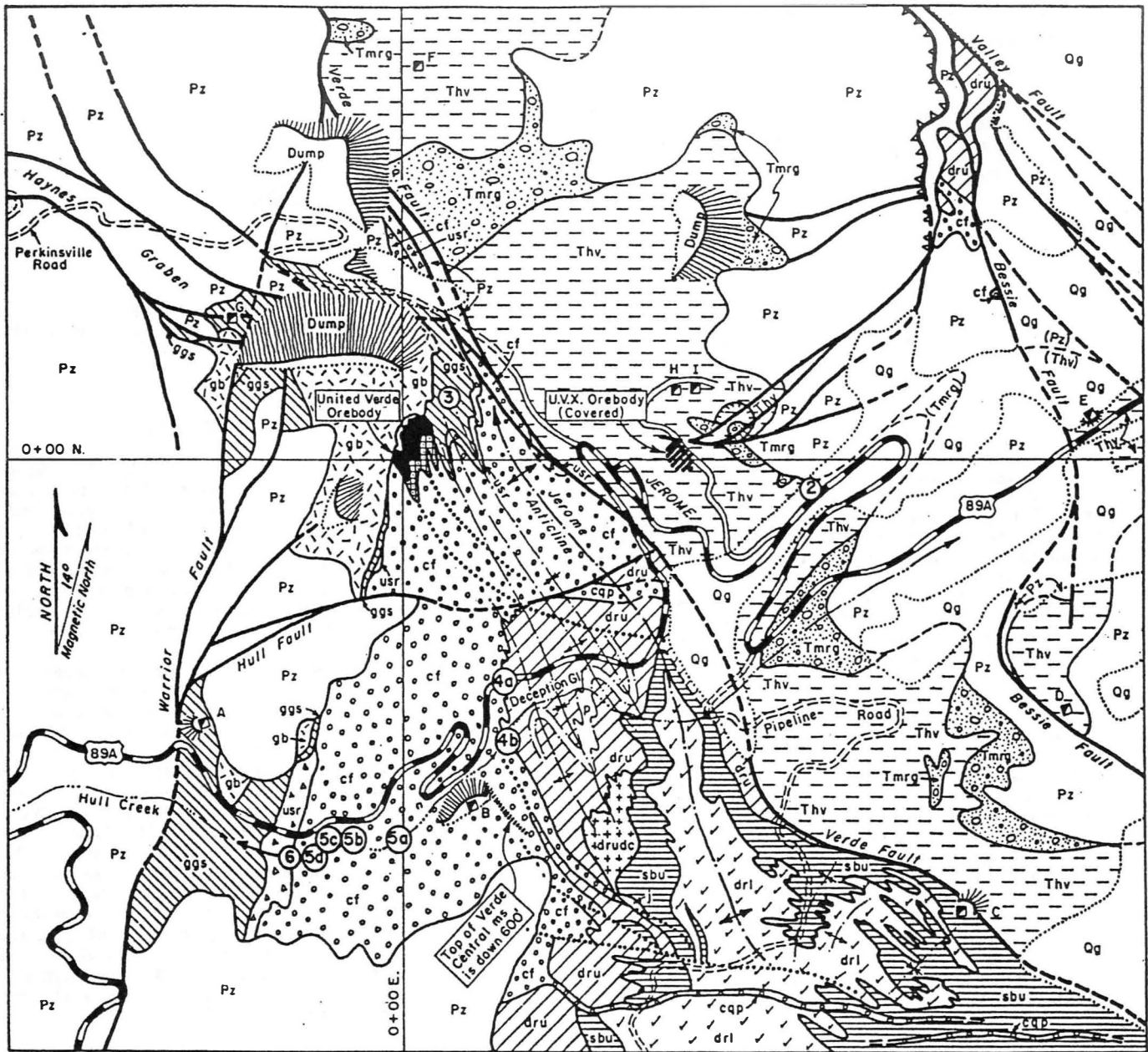
Scale: 0 1000 2000 3000 4000 Feet

0 250 500 750 1000 1250 Meters

4a) Field-Trip Stops

Figure 2. Simplified geologic map of the Jerome area, Verde district, Yavapai County, Arizona (modified from Lindberg, 1986a). Post-1971 detailed contact mapping modifies the interpretations and nomenclature of Anderson and Creasey (1958) and Anderson and Nash (1972). Current informal district usage is given below.

MAP SYMBOLS:

▨ Shafts: A=Jerome Grande, B=Verde Central,
C=Verde Combination, D=Gadsden, E=Texas,
F=A&A, G=Haynes, H=Edith & I=Audrey
✖ F₁ Folds (NNW) & F₂ "Cross Folds"
⋯⋯⋯ Proterozoic Cauldron Faults
━━ ━ ━ Tertiary Faults; Laramide/Miocene

PHANEROZOIC ROCKS:

	Qg	Quaternary Alluvium
	Thv	Miocene Hickey Basalt
	Tmrg	Pre-Miocene Conglomerates
	Pz	Paleozoic Sediments; Undiff.

PROTEROZOIC ROCKS:

	gb	Synvolcanic Intrusive Gabbro Sill
	ggs	Grapevine Gulch Fm; Volcaniclastic Sediments, Tuffs
	usr	Upper Succession Rhyolite/Dacite Domes & Breccias
	ms	United Verde & U.V.X. (Concealed) Massive Sulfides
	bs	Mg-Chlorite Alteration Zone ("Black Schist")
	cf	Cleopatra Formation; Undiff. Rhyodacitic Extrusive
	cqp	Cleopatra Quartz Porphyry Dikes
	ms	Verde Central Massive Sulfide Horizon
	dru	"Upper Deception Rhyolite" with Polygonal Flow .(p)
	drudc	Dacitic Dome within "Upper Deception Rhyolite"
	sbu	"Upper Shea Basalt"; Includes Minor Rhyolitic Strata
	drl	"Lower Deception Rhyolite" Flows & Breccias

The geology and ore deposits of the Jerome area were described by Anderson and Creasey (1958) and they assigned the Precambrian rocks of the Verde district to the Ash Creek Group of the Yavapai Series. Silver and coworkers (Anderson and others; 1971) later dated these rocks at 1820 ± 10 Ma. At that time the massive sulfide ore deposits at Jerome were believed to be replacement bodies. A quartz porphyry intrusion into the volcanic and sedimentary stratigraphy was thought to have been the principal agent responsible for ore formation. One of the earlier published accounts in Arizona that challenged the replacement concept was a paper by Gilmour and Still (1968), who proposed a volcanogenic origin for the Iron King massive sulfide ores at Humboldt. That deposit is located 20 miles to the southwest of Jerome and is hosted in similar-age volcanic rocks.

The volcanogenic model for the Jerome orebodies was well established by 1971 (P.A. Handverger, pers. comm.). Detailed post-1971 contact mapping and structural analysis reveal that the stratigraphic nomenclature of Anderson and Creasey (1958) needs revision. There are two main reasons for this. First of all is the recognition of multiple strata repetitions on fold limbs within the Jerome anticlinorium (Lindberg and Jacobson, 1974) that were not previously recognized. Secondly, Anderson and Nash (1972) reinterpreted the the former quartz porphyry to be an extrusive crystal tuff and defined it as the Cleopatra Member of the Deception Rhyolite. Geologic usage shown in Figure 2 is based on the informal stratigraphy given by Lindberg (1986a), and is further modified by the redefined Cleopatra Formation of Gustin (pers. comm.). Gustin has concluded that the Cleopatra Formation is largely composed of rhyodacitic extrusive rocks. This ore-associated Cleopatra Formation is further described during Stop 5.

The oldest rocks in the district are massive to pillowed basalts that are exposed in the core of the Jerome anticlinorium and located just south of the coverage shown in Figure 2. Conformably overlying the "Shea" basalts are rhyolites, dacites, and basalt flows that were formerly included within the Deception Rhyolite. These are overlain by a series of rhyolitic flows and breccias that form the prominent outcrops in Deception Gulch, just south of Jerome along Highway 89A. Because of the north-northwest-plunging folds, these rock exposures generally become younger toward the north.

Submarine hot springs formed on the top surface of this series of rhyolitic flows, as evidenced by the thin massive sulfide ore lenses found at the Verde Central mine. Lindberg (1986a) infers that an abrupt cauldron collapse of the tumescent submarine volcanic pile occurred simultaneously with the rapid eruption of the voluminous Cleopatra Formation. Numerous field relationships along the quartz porphyry feeder dikes and cauldron faults (all prefolding) show down-to-the-north lithologic offsets. One set of cauldron offsets and feeder dikes can be seen in the lower portion of Figure 2.

Shortly after consolidation of the lower member of the Cleopatra Formation, as defined by Gustin in Figure 5, additional cauldron faulting is interpreted by Lindberg (1986a) to have cut through the entire volcanic pile and extended well into the underlying rhyolites. The Dillon tunnel followed one mineralized and chlorite-altered fracture zone from the base of the United Verde orebody into the rhyolite flows of Deception Gulch.

Hydrothermal solutions vented from the sea-floor fracture zones and massive sulfides were precipitated at the sites. Widespread footwall alteration of the Cleopatra Formation resulted from an intense hydrothermal system. The most concentrated alteration can be seen at the immediate base of the United Verde ore deposit where rock replacement by Mg-rich chlorite reaches a climax in the fractured Cleopatra footwall. The miners called this rock "black schist." Similar alteration zones are seen at the U.V.X. orebody as described by Handverger (1975). A recent study of trace-element mobility in the Cleopatra crystal tuff has been made by Lesher and others (1986).

In the vicinity of the United Verde orebody, postore rocks include volcaniclastic sediments, minor cherts, rhyolitic/dacitic flows, tuffs, and breccias, and andesitic flows and hyaloclastites. Further south along Highway 89A and Hull Creek, the postore rock succession includes the upper member of the Cleopatra Formation, as defined by Gustin (Ph.D. thesis in prep.), as well. The post-Cleopatra rocks at this location also include small blister domes, breccias, and tuffs of dacitic to rhyolitic composition that are, in turn, covered by a thick series of volcaniclastic turbidites included within the Grapevine Gulch Formation (Anderson and Creasey, 1958). Synvolcanic gabbro sills were intruded into the postore succession prior to folding. The alteration state of postore rocks is generally very low compared to preore volcanic rocks.

A depositional hiatus of 1.3 b.y. marks the unconformity between the folded Precambrian and flat-lying Paleozoic cover rocks. Deep valleys were cut into the Paleozoic rocks during post-Laramide erosion of the uplifted terrane. Hickey Basalt, dated at 10-15 Ma by McKee and Anderson (1971), covers pre-Hickey conglomerates, which fill the channels.

STRUCTURAL GEOLOGY

All Proterozoic volcanic, sedimentary, and synvolcanic intrusive rocks of the Verde district are penetratively deformed into similar folds with steep, subparallel axial planes. Fold amplitudes (F_1) exceed 6000 feet. In the Jerome area the F_1 folds strike north-northwest with the axial planes dipping steeply toward the east-northeast. The primary folds in the United Verde deposit plunge northerly at 60°. "Cross folds" (F_2) intersect the primary set at nearly right angles, creating fold plunge reversals and the complex "Christmas tree" interference patterns seen in the southeast corner of Figure 2.

Precambrian faulting is mainly restricted to pre-ore cauldron faults that are directly related to the ore-forming process. All known Precambrian faults were formed prior to the onset of Proterozoic folding. High-angle reverse faulting occurred during the uplift of the region in Laramide time, but normal faulting did not occur in the district until the Verde graben began to form about 10 Ma (Lindberg, 1983, 1986a).

STOP 1

Stop 1, near the Cottonwood airport, is for orientation purposes. The exposed Proterozoic rocks occupy the middle slopes of Mingus Mountain to the west of the observer and are overlain by Paleozoic sediments and Tertiary basalts. The Verde fault marks the break in slope along the western edge of the Verde graben. The Precambrian surface is estimated to lie about 3500 feet below the airport, with a total offset in excess of 6100 vertical feet.

178

Stop 2 is located at a pullout along Highway 89A just west of the old Mingus Union High School on the east side of town. The Verde fault passes through the upper part of Jerome and separates the bold Precambrian exposures of Cleopatra Hill from the downfaulted block where the observer is standing. The fault displacement is about 1500 feet at this point. About 2000 feet to the northwest are the headframes of the U.V.X. mine (Edith and Audrey shafts). The bonanza-grade U.V.X. orebodies, now mined out, were located about 1000 feet due south of the shafts, or just north of the old "Powderbox Church" (solitary building just above the access road leading to the mine and museum area). The cave zone just south of the white building at the Jerome State Park Museum lies to the east of the deposit and was used to backfill mined-out U.V.X. stopes.

Figure 3 shows an east-west cross section that passes 500 feet to the north of Stop 2. The observer is situated just in front of the right edge of the figure. The section crosses the Jerome anticlinorium and shows the opposite-facing and separate United Verde and U.V.X. massive sulfide orebodies. Depth of oxidation at the U.V.X. deposit is nearly 500 feet, which exceeds the typical depth of weathering beneath the pre-Paleozoic unconformity. Part of the supergene enrichment of the U.V.X. ores is post-Laramide in age.

Stop 3 will be at the United Verde open pit. Permission from Phelps Dodge Corporation is required to enter the pit area. The large flat bench leading into the pit was the former 300-foot level of the underground mine.

At the pit edge the observer is standing near the apex of an anticlinal drag fold in the Cleopatra Formation footwall. The Cleopatra has conspicuous quartz phenocrysts that are set within an intensely sericitic matrix. Across the pit, where most of the massive sulfide body has been mined away, the massive pyrite at the top of the deposit can still be seen. Overlying the laminated to massive pyrite (poor in copper values) is a highly folded jasper caprock and thin remnants of postore volcaniclastic sediments of the Grapevine Gulch Formation. The bold western wall is composed of a large synvolcanic gabbro sill. The sill mainly intruded and dilated the postore sedimentary section and bleached some of the jasper to a whitish "quartz" (miner's term). Looking toward the southwest, at the southernmost part of the pit, the observer can see the darker, Mg-rich chloritic Cleopatra footwall ("black schist"), which plunges at 60° to the north-northwest. This alteration zone directly underlies the zone of highest grade copper ores that were mined out. Flanking the chloritic footwall alteration zone, with its chalcopyrite veins
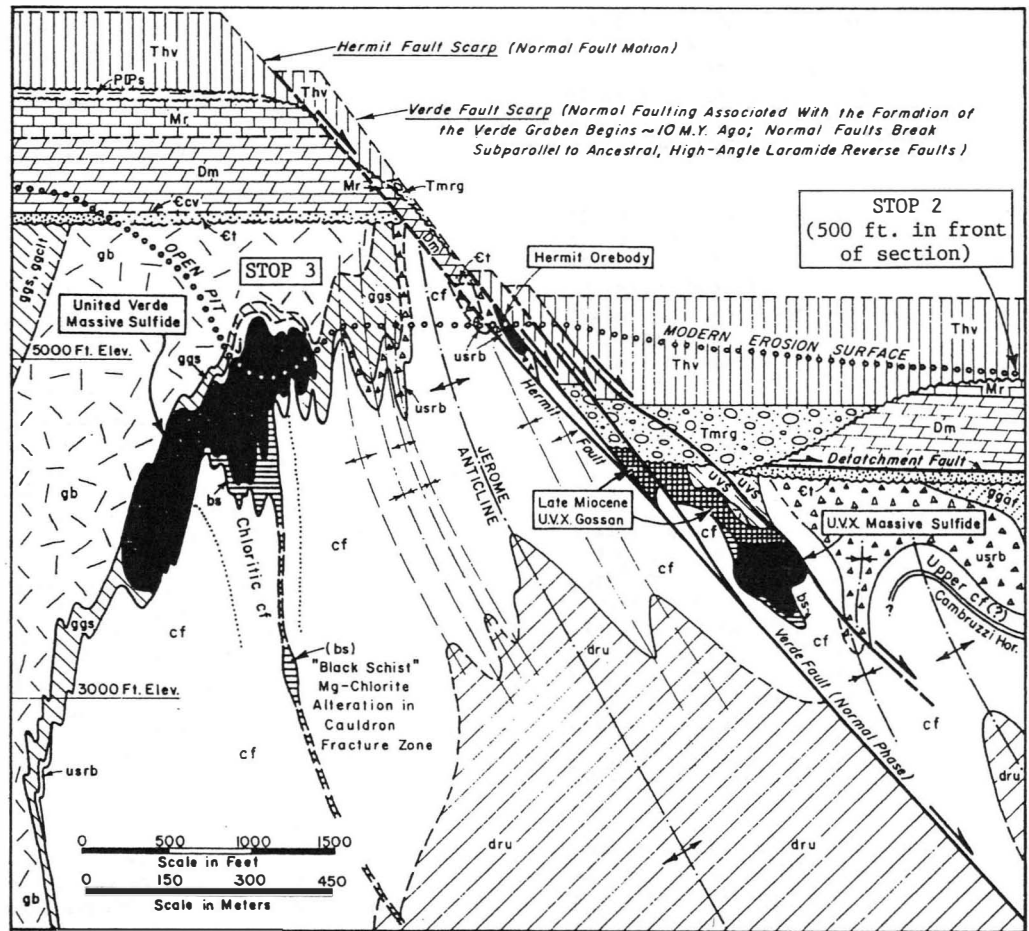

Figure 3. East-west cross section, looking north, through the Jerome anticlinorium. Geologic notations are given in Figure 2. The time is about 10 Ma when normal Verde graben faulting began. The United Verde and U.V.X. are separate orebodies which are now located on opposite limbs of the fold system.

and stockworks, are yellowish zones of sericitized Cleopatra Formation containing disseminated pyrite. The westernmost wall of Cleopatra, which divides the dominantly chloritic and sericitic alteration zones, is thought to represent a preore sea-floor fault scarp associated with cauldron fracturing (Lindberg, 1986a). To the immediate south of the pit edge are two tight synclines, which contain cherty exhalites, and postore rhyolitic tuffs and volcaniclastic sediments. Banded exhalites, time-equivalent to the ore horizon, are somewhat distal to to vent site. The ore horizon lies at the apex of the Cleopatra at this point.

The orebody was mined down to the 4500-foot mine level (4200 feet below the pit edge). Below the 2400-foot level the deposit began to thin and spread out into discrete lenses. Figure 4 shows the distribution of copper within a typical level in the United Verde mine. The best copper ore was located in the basal portion of the massive sulfide body as well as in the chloritic Cleopatra footwall. This represents a late-stage hydrothermal replacement that was most intense at the base of the earlier formed, syngenetic massive sulfide body that overlies the venting site.
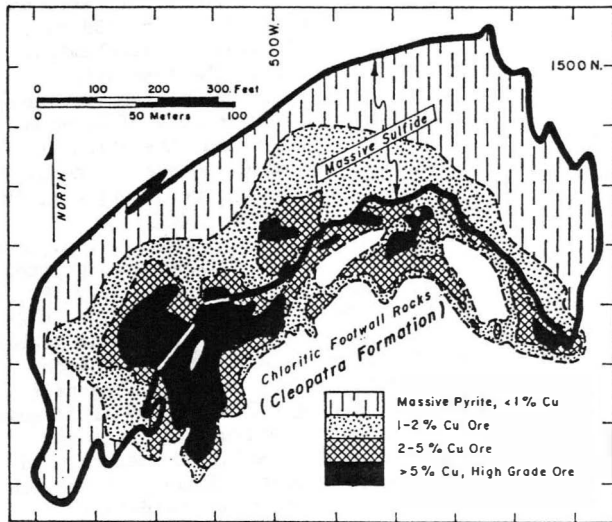

Figure 4. Distribution of copper on the United Verde 2400-foot level. Much of the copper ore lies below the massive sulfide layer. (Adapted from Anderson and Creasey, 1958, fig. 17, p. 117.)

STOP 4

Stop 4 will examine two locations at the contact between the highly folded and fine-grained rhyolitic flows of Deception Gulch and the overlying Cleopatra Formation. Stop 4a will examine the upper portion of the Deception Rhyolite flows and breccias (Anderson and Creasey, 1958). Sedimentary horizons are absent within this thick series of flows. Stop 4b is located along a drag-folded contact between these rhyolitic flows and the overlying massive Cleopatra Formation. The contact is marked by a thin Mg-chloritic altered layer, thin sedimentary beds, jasper lenses, and foot-wall jasper veinlets, which give evidence of a pre-Cleopatra mineralization event. The blind massive sulfide ores of the Verde Central mine are located a short distance to the south of this point. Between 1928-1930 this small mine produced about 140,000 short tons of 2.7% copper ore. Mineral associations seen at Stop 4b are excellent indicators of potential ore.

STOP 5
(by Mae Sexauer Gustin)

At this stop the rhyodacitic rocks associated with the United Verde deposit, previously named the Cleopatra Member of the Deception Rhyolite (Anderson and Nash, 1972), will be examined. Previous workers in the Jerome area, i.e., Anderson and Creasey (1958), Anderson and Nash (1972), and Lindberg and Jacobson (1974), did not define mappable stratigraphic units within the Cleopatra Member. Norman (1977) attempted to do so by dividing the rock types into uniform and nonuniform quartz-feldspar porphyry. His mapping did not produce a coherent stratigraphy.

As a result of recent work by Gustin (1986; in prep.), it is proposed that the Cleopatra Member as defined by Anderson and Nash (1972) be renamed the Cleopatra Formation and that it be divided into two distinct members, the upper (UC) and lower (LC). This subdivision, shown in Figure 5, is based in large part on detailed mapping of alteration facies within the Cleopatra Formation. The contact between the LC and UC is the lateral continuation on the United Verde ore horizon. This horizon had previously been interpreted to lie between the Cleopatra Formation and the Grapevine Gulch Formation and/or Upper Deception Rhyolite (Anderson and Nash, 1972; Lindberg and Jacobson, 1974).
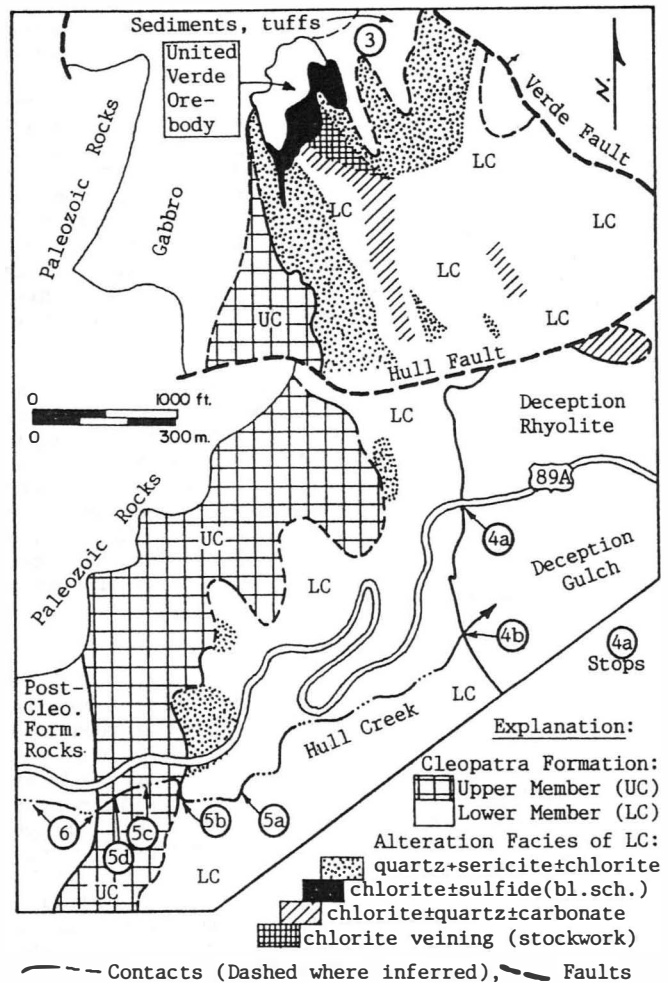

Figure 5. Geology of the Cleopatra Formation by Mae Sexauer Gustin. The upper and lower boundaries of the formation and faults are taken from Anderson and Creasey (1958).

The LC and UC are represented by flows, volcaniclastic and vitroclastic tuffs, volcanic breccias, and volcaniclastic sediments that contain abundant quartz and feldspar phenocrysts. The LC is massive immediately beneath the orebody with breccias increasing in abundance to the south. This implies that the LC immediately beneath the orebody may have been a dome with slump and talus breccias being deposited to the south. The UC consists of abundant breccias, flows, and a large component of quartz-feldspar tuffs. The contact between the LC and UC is marked by changes in alteration facies and by a unique quartz-sericite-chlorite-carbonate tuff, hematitic cherts, and volcaniclastic sediments at the immediate base of the UC.

Within the LC, north of the Hull fault, feldspars are destroyed and some are pseudomorphed by coarse-grained quartz. The alteration varies from complete chloritization to sericitization and silicification (Figure 5). South of the Hull fault the LC contains feldspars and is variably silicified and chloritized (Stop 5a). The contact between the LC and UC, as exposed along Hull Creek, is marked by deformed volcaniclastic sediments, hematitic cherts, and hematitic veining (Stop 5b).

The UC contains rocks that are much less altered than those in the LC. Alteration is represented in the UC by the mineral assemblage of hematite ± quartz ± carbonate ± chlorite. The UC chlorites may be distinguished from those in the LC by a lighter green color and $Fe/Fe+Mg > 0.48$ versus the dark green to black color and $Fe/Fe+Mg < 0.48$, characteristic of the LC. Hematitization is represented by veining (replacement and open-space fillings),
(producing purplish quartz-feldspar porphyries), and disseminated hematite found in the matrix of various UC rocks. Veining and pervasive hematitization may be seen along Hull Creek (Stop 5c). A rock that is found within the UC is called "mottled" rock. This outcrops at and below Stop 5d where a coarse breccia contains irregular pink fragments set within a grey matrix. Hematite is present in both domains, but is predominant in the pink areas.

Thus, the LC is distinguished from the UC by the type of chlorite present, the abundance of sericite and secondary silicification, and the lack of feldspar in areas of intense alteration. The uppermost portion of the LC contains patchy zones of chloritization and silicification, which often immediately underlie the contact with the UC. Sediments and/or a distinctive tuff may lie at the base of the UC and the rocks directly above the contact are hematitized and often appear unaltered.

STOP 6

Stop 6 is located at the top of the Cleopatra Formation along Hull Creek. Thin, finely banded, and purplish sediments, minor tuffaceous sediments, and rare jasper lenses cover the Cleopatra. Local blister domes and breccias of dacitic to rhyolitic composition conformably overlie the thin sediments. Further upstream are superb exposures of cyclic turbidite sheets composed of volcaniclastic sediments. These rocks are included within the Grapevine Gulch Formation of Anderson and Creasey (1958). Jasper lenses and/or angular rip-up clasts of jasper or grey chert at the base of a turbidite cycle indicate that minor chemical exhalites were still being formed atop the volcanic pile. Lindberg (1986a) infers that the center of volcanic activity lies somewhere to the north of Jerome.

REFERENCES CITED

Anderson, C.A., Blacet, P.M., Silver, L.T., and Stern, T.W., 1971, Revision of Precambrian stratigraphy in Prescott-Jerome area, Yavapai County, Arizona: U.S. Geological Survey Bulletin 1324-C, p. 1-16.

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.

Anderson, C.A., and Nash, J.T., 1972, Geology of the massive sulfide deposits at Jerome, Arizona – a reinterpretation: Economic Geology, v. 67, no. 7, p. 845-863.

Gilmour, P., 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: American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 2, 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, B., and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 339-342.

————in preparation, A petrological, geochemical, and stable isotope study of the alteration associated with the United Verde orebody, Jerome, Arizona [Ph.D. thesis]: University of Arizona.

Handverger, P.A., 1975, Geology and alteration of the United Verde Extension mine, Jerome, Arizona: American Institute of Mining, Metallurgical, and Petroleum Engineers, Preprint, 26 p.

Lesher, C.M., Lindberg, P.A., and Campbell, I.H., 1986, Trace element mobility in the Cleopatra crystal tuff, Jerome, Arizona: Geological Society of America Abstracts with Programs, v. 18, p. 672.

Lindberg, P.A., 1983, Development of the Verde graben, north-central Arizona [abs.]: Arizona-Nevada Academy of Science, Annual Meeting, Flagstaff.

————1986a, A brief geologic history and field guide to the Jerome district, Arizona, in Nations, J.D., and others, eds., Geology of central and northern Arizona: Geological Society of America, Rocky Mountain Section Meeting, Guidebook, p. 127-139.

————1986b, Geology of the Copper Chief mine, Jerome district, Arizona, in Beatty, B., and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Arizona Geological Society Digest, v. 16, p. 343-349.

Lindberg, P.A., and Jacobson, H.S., 1974, Economic geology and field guide of the Jerome district, Arizona, in Karlstrom, T.N.V., and others, eds., Geology of northern Arizona, with notes on archaeology and paleoclimate; pt. 2, area studies field guides: Geological Society of America, Rocky Mountain Section Meeting, Flagstaff, Arizona, p. 794-804.

McKee, E.H., and Anderson, C.A., 1971, Age and chemistry of Tertiary volcanic rocks in north-central Arizona and their relationship to the Colorado Plateau: Geological Society of America Bulletin, v. 82, p. 2767-2782.

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

pervasive hemat

13

PRECAMBRIAN ORE DEPOSITS OF ARIZONA

by
Paul A. Lindberg
Sedona, Arizona 86336

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 exhalitive 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
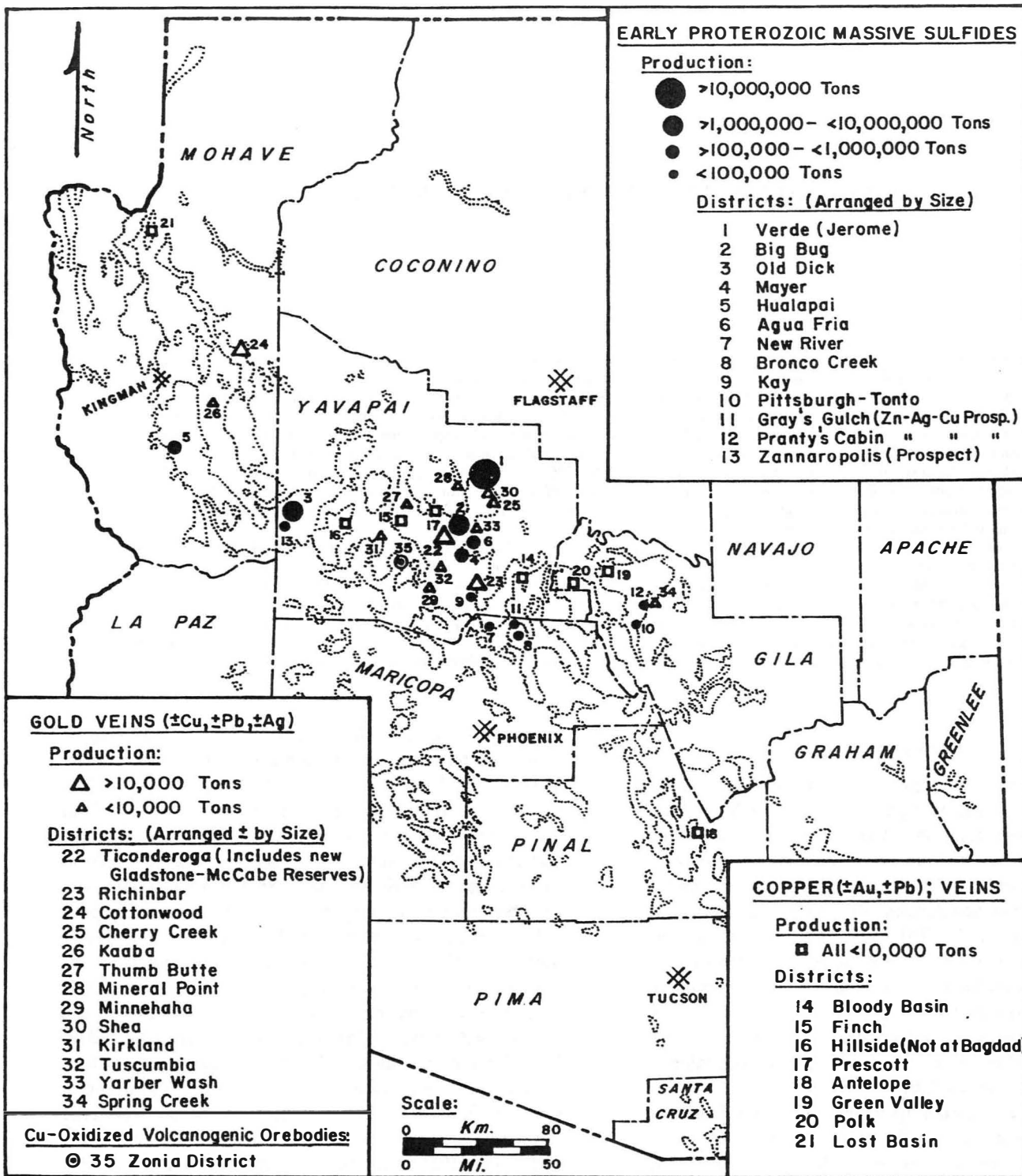
Figure 1. Location map of outcropping Early Proterozoic rocks in Arizona (dotted outline), which shows principal base- and precious-metal mining districts of Precambrian age. Ore classification and age of deposit are largely adapted from the usage established by Keith and others (1983) and Welty and 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: [a]Compiled from Phelps Dodge Corp. and Verde Exploration Co. data.; see table 2.
[b]Uses only the statistics for the Iron King mine by Lawrence and Dixon (1986).
[c]Refer to table 3.
[d]Includes 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 south-western 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
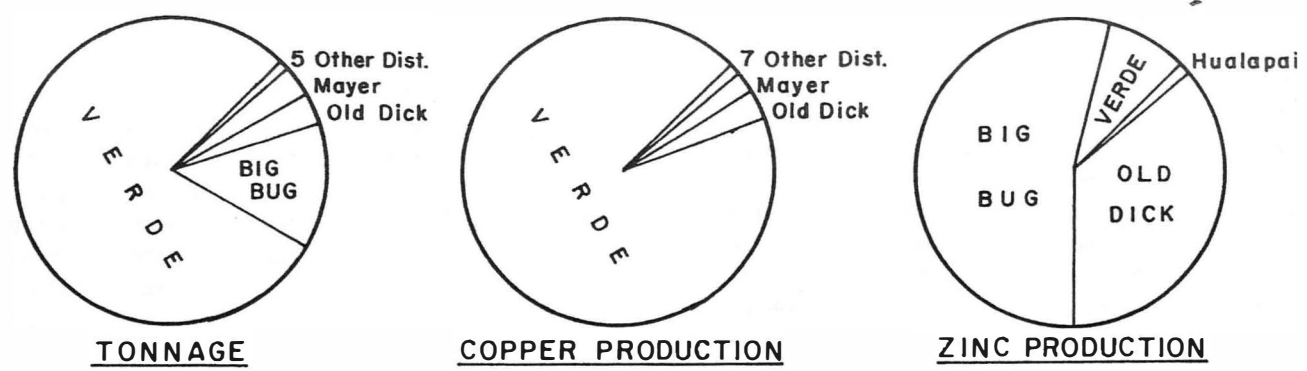
Figure 2. Comparison of ore tonnage and copper and zinc production from massive sulfide districts in Arizona from 1893 to 1977 (excludes possible reserves). The greatest contrast between districts can be seen in the dramatic difference in the metal content of the ores from the Verde and Big Bug districts, 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 chalcopyrite 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 chalcopyrite, 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: [a]Estimated 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.

[b]Computed from grades given by Conway (1986).

[c]Extrapolated 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[a])
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 Au
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: [a]Data from Stan West Mining Corp. 1985 Annual Report.
[b]A 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
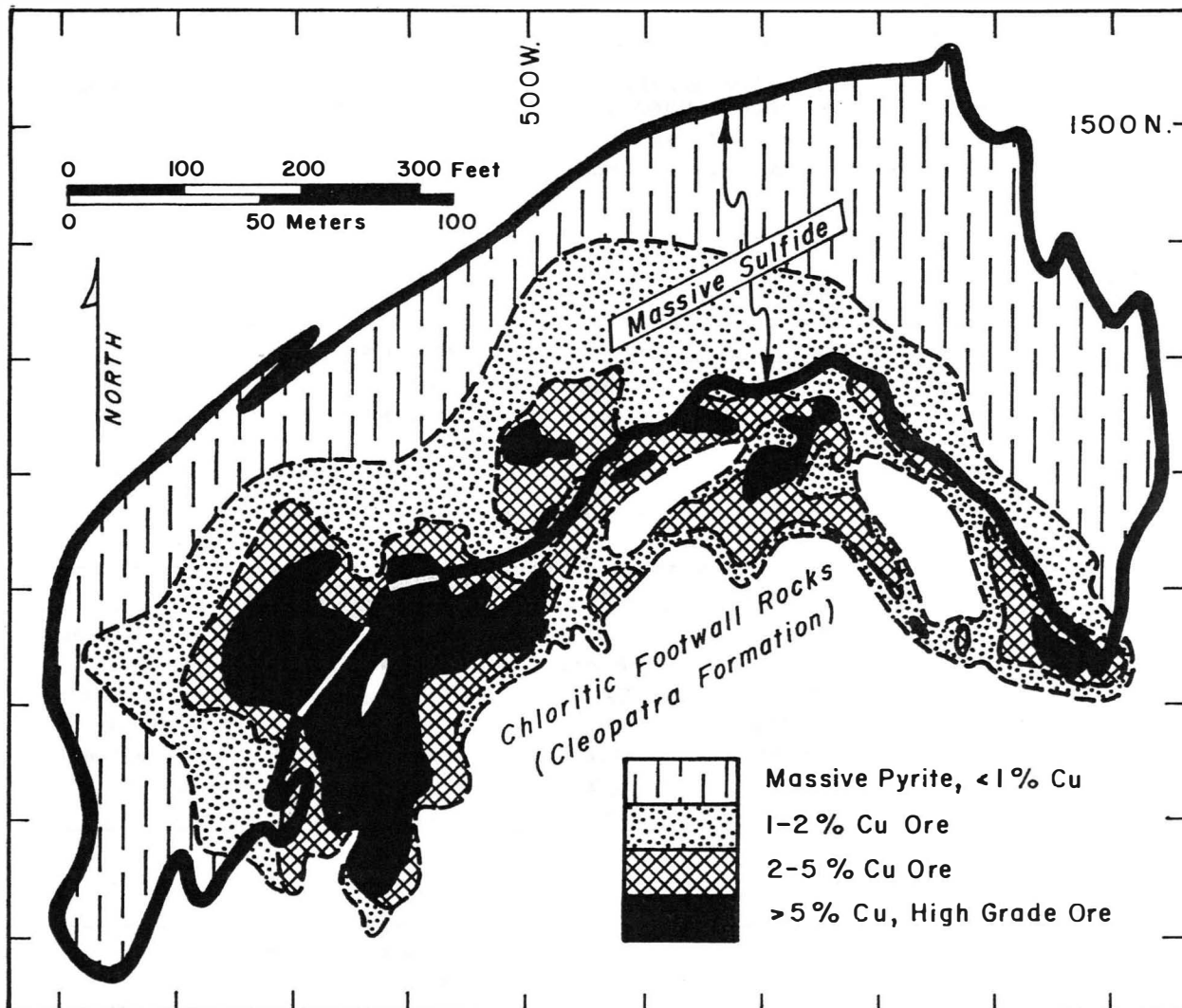

Figure 3. Plan map of the United Verde 2,400-ft level showing distribution of copper mineralization relative to the massive sulfide body. The heavy outline shows the outer boundary of the large pyritic body; the copper values in the stratigraphic hanging wall are very low. Copper mineralization is most 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

Exposed Proterozoic Rocks, Yavapai County

- Granitic Intrusives, Undifferentiated
- Gabbroic Intrusives; Mostly Synvolcanic Bodies
- Dominantly Meta-Volcaniclastic, Tuffaceous, and Sedimentary Rocks; Bedded; Often Schistose
- Dominantly Rhyolitic Flow/Intrusive Complexes; Includes Some Dacites, Andesites, and Tuffs
- Dominantly Basalt and Andesite Flows, Tuffs, and Hyaloclastites

NORTH

0 mi. 6
0 km. 10

MINERAL DEPOSITS

1 United Verde
2 United Verde Extension
3 Verde Central
4 Cliff
5 Copper Chief
6 Yaeger
7 Iron King
8 McCabe-Gladstone
9 Lone Pine
10 Boggs
11 Butternut
12 Hackberry
13 Copper Queen
14 Binghampton
15 Stoddard
16 Blue Bell
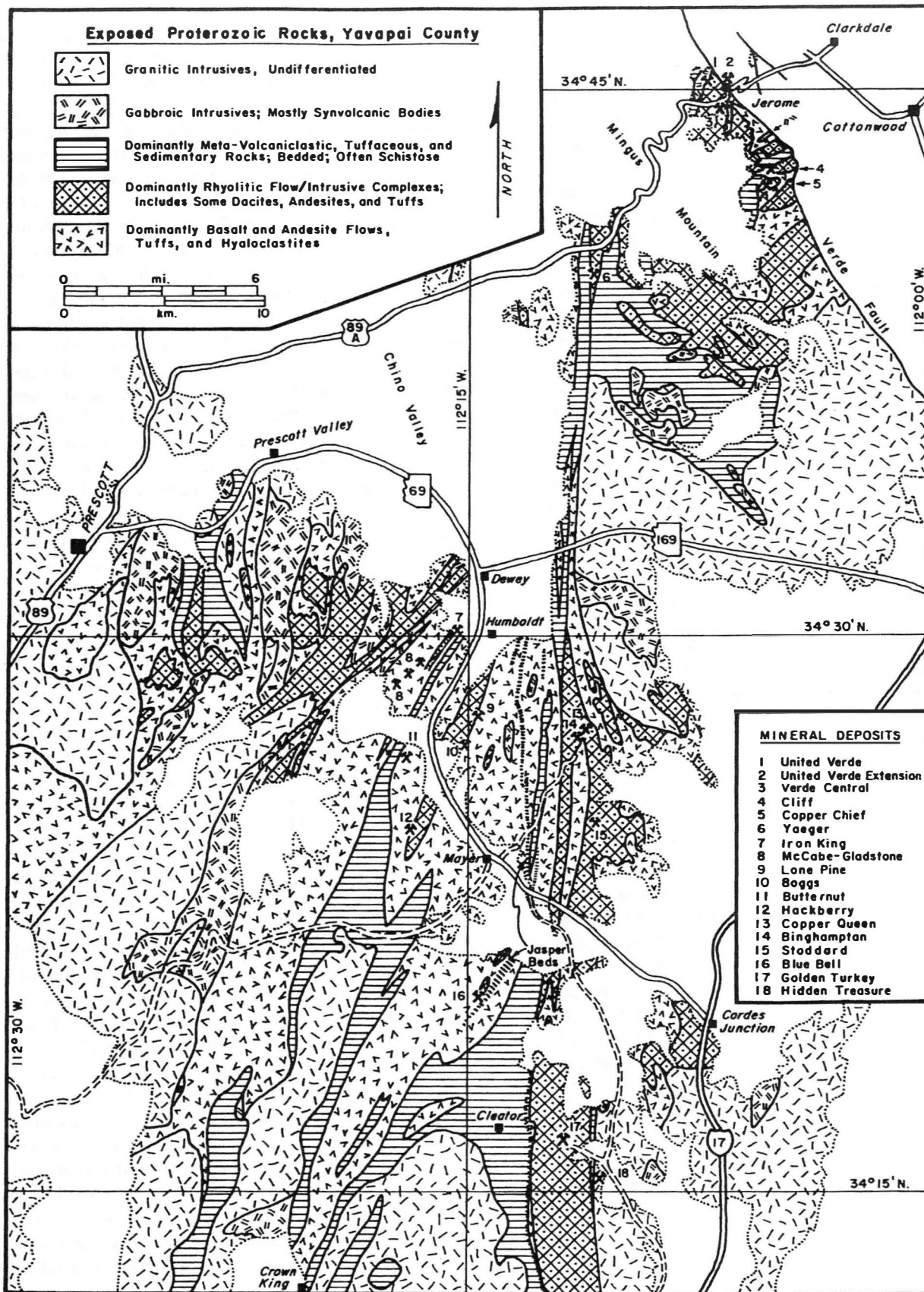17 Golden Turkey
18 Hidden Treasure

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 exhalitive 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 chalcopyrite 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
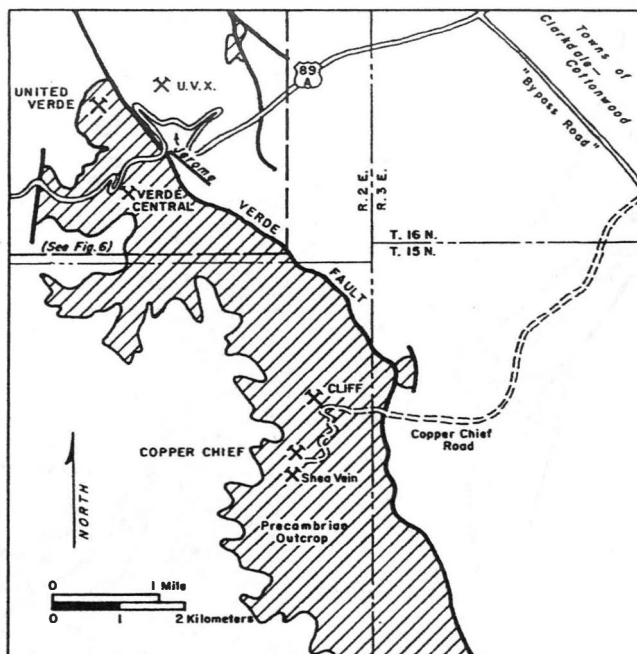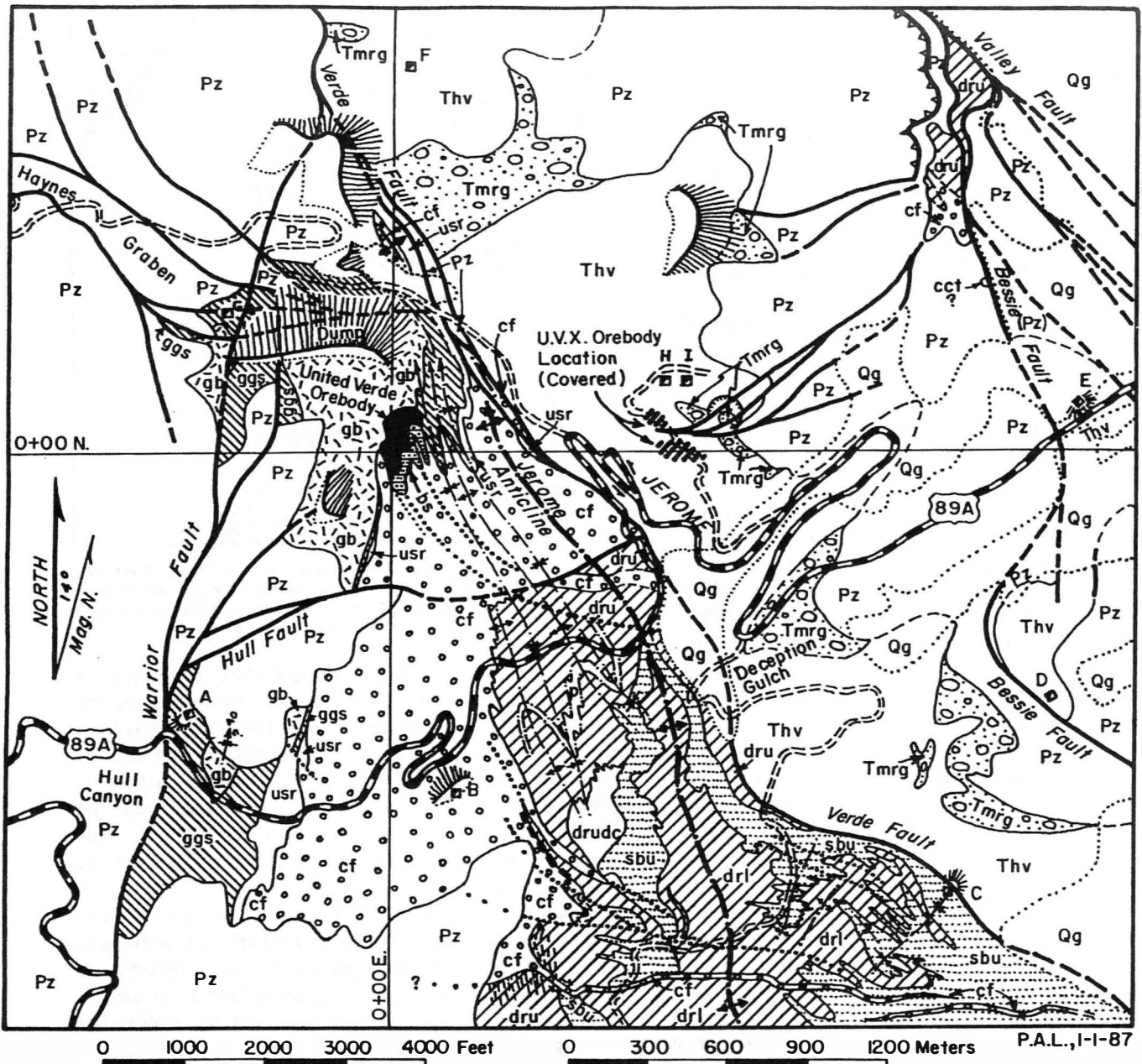

Figure 5. Location map of Precambrian rock exposures and formerly producing mines in the Verde district, Yavapai County, near Jerome, Arizona. Heavy lines show some of the Tertiary faults that are in contact with Early Proterozoic volcanic and sedimentary rock suites.

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.

Rock types:

Thv   Mid.-late Miocene, Hickey basalt
Tmrg   Eocene(?)-mid. Miocene, "Mogollon Rim gravels"
Pz   Paleozoic sediments, undifferentiated
gb   Gabbro sills
ggs   Grapevine Gulch fm.; flows, hyaloclastites, turbidites
usr   Upper succession rhyolite (post-United Verde m.s.)
ms/exh/uvs Massive sulfide, chemical exhalites, and lateral
       time-equiv. sediments; United Verde ore-forming event
bs   "Black schist" (Mg-chloritic alteration of ore footwall)
cf   Cleopatra formation (rhyodacitic extrusive rocks)
ms   Massive sulfide; Verde Central ore-forming event
dru   Upper Deception rhyolite; includes polygonal flow
       marker horizon(p) and dacite dome (drudc)
sbu   Upper Shea basalt; includes minor rhyolite beds
drl   Lower Deception rhyolite

Map symbols:

▨   Mine shafts: A, Jerome Grande;
     B, Verde Central; C, Verde Com-
     bination; D, Gadsden; E, Texas;
     F, A&A; G, Haynes; and U.V.X.
     Edith (H) and Audrey (I)

☀   Mine dumps

⚒   Folds; F₁ (N.N.W.)& F₂ "cross folds"

⋯⋯⋯ Proterozoic cauldron faults;
     ore-related; pre-folding

━━━ Late Miocene normal faults;
     re-activated Laramide faults

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 F_1 fold axes. Steep F_2 "cross folds" trend at right angles to the F_1 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 chalcopyritic ore and footwall chloritic
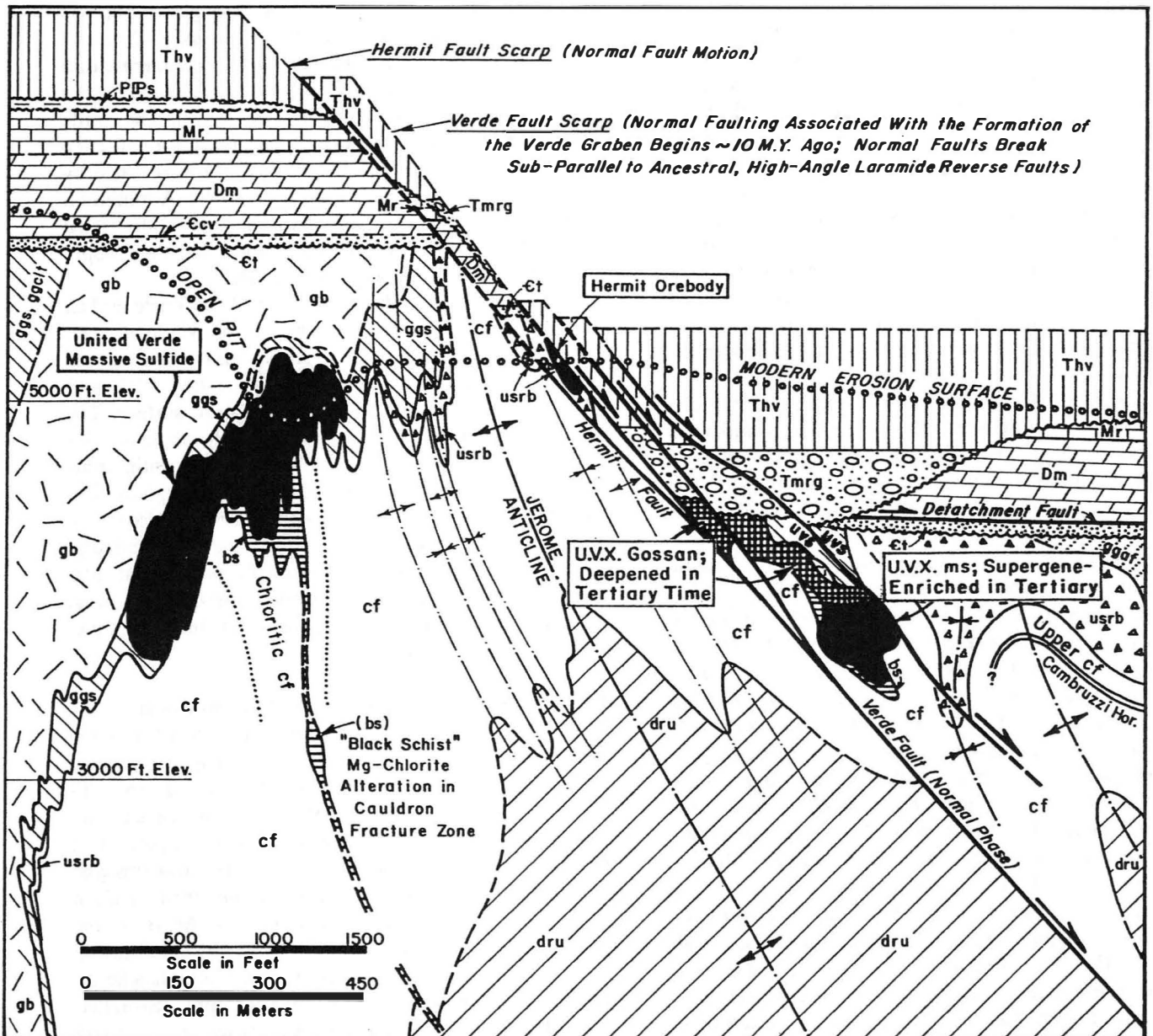

Figure 7. East-west composite cross section through the Jerome anticlinorium with the United Verde and U. V. X. orebodies located on opposite limbs. Each orebody rests on the surface of the rhyodacitic Cleopatra formation (cf) and has its own Mg-rich chlorite alteration zone. The legend for figure 6 gives the rock names and abbreviations. Postore rocks include volcaniclastic sediments, minor rhyolitic breccias and tuffs, andesitic or basaltic flows and hyaloclastites, and a synvolcanic intrusive gabbro sill. Footwall rocks show widespread sericite alteration of feldspars and intense Mg-chlorite alteration directly below the massive sulfide ores. Failure along Laramide and late Miocene faults mirrors the F_1 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, volcaniclastic 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
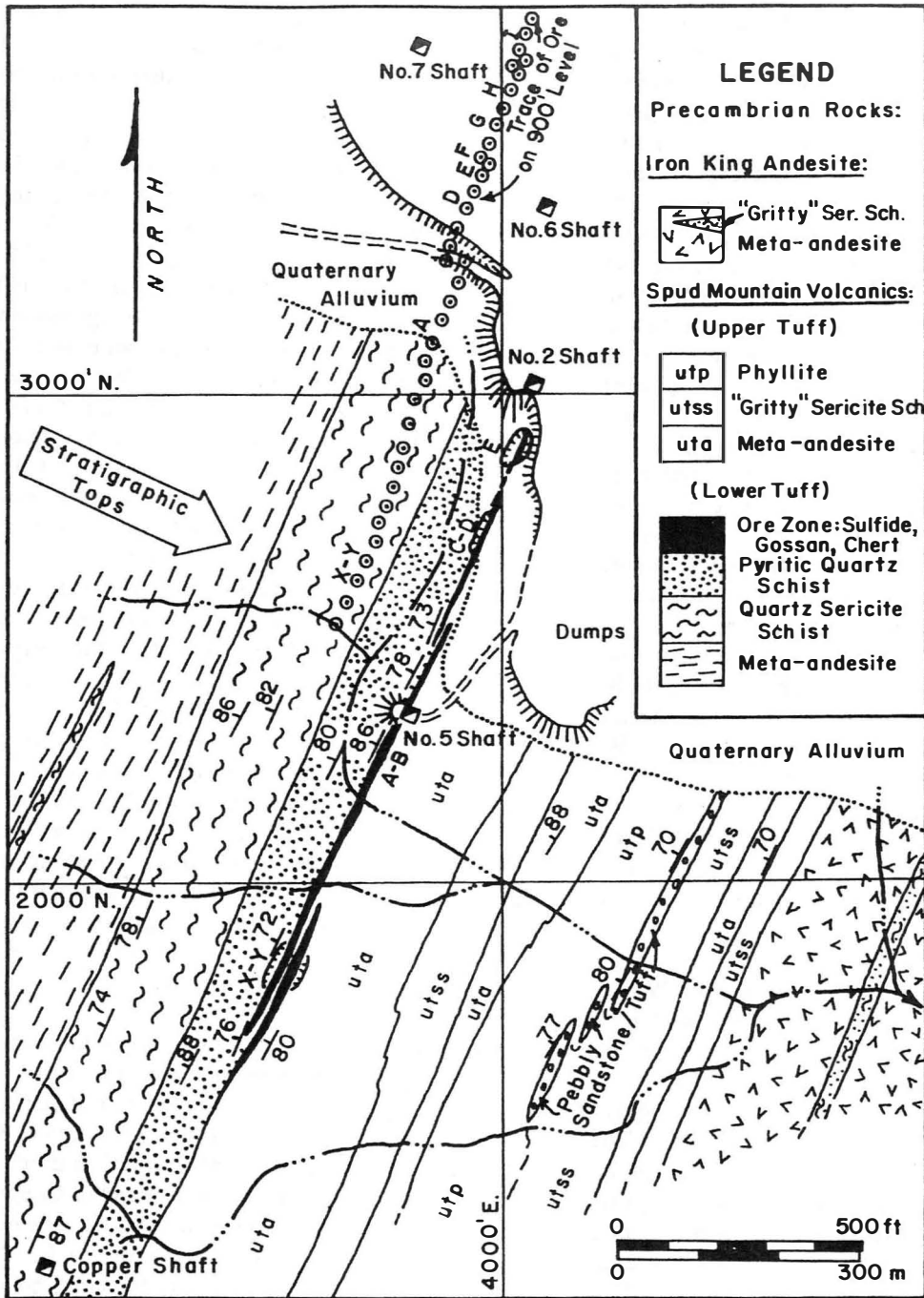
Figure 8. Geologic plan map of the surface outcropping of the Iron King deposit, Humboldt, Arizona. The individual ore lenses are lettered and can be seen at their surface locations and their plunge positions on the 900-ft mine level. The ore horizon is steeply overturned. Refer to the longitudinal cross 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.
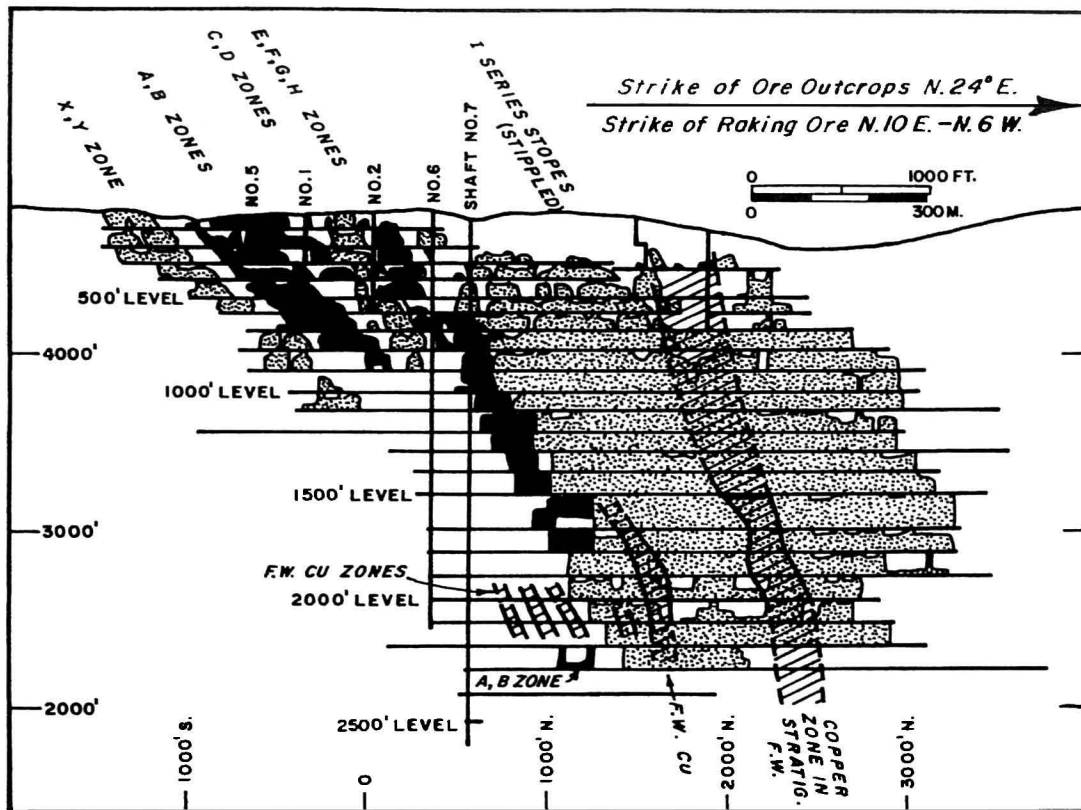
Figure 9. Composite longitudinal section through the Iron King mine workings, facing west-northwest. The stoped areas are shown by alternating stippled and solid color. Disruptions in ore zones probably result from shear faulting of the stratiform sulfide body at north-plunging chevron fold crests. There 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 volcaniclastic 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

2 8

Scale:

0 — 1000m
0 — 4000ft

78 ⤢ Overturned beds

▬▬ Faults

EARLY PROTEROZOIC ROCKS:

	gr	Granitic rocks
	g	Gabbro
	a	Alaskite
Undiff.	f	Felsic tuffs, flows, sed.
Dick Rhyolite	r	Extrusive rhyolite
	ir	Intrusive rhyolite
Undiff.	m	Mafic volcanic rocks
	bc	Intermediate clastic rocks
Bridle Form.	ba	Mafic agglomerate, tuffs
	b	Mafic flows, pillow basalt, hyaloclastites

MINES (Massive Sulfide Deposits:

CK   Copper King
OD   Old Dick
B   Bruce
CQ   Copper Queen
R   Rudkins
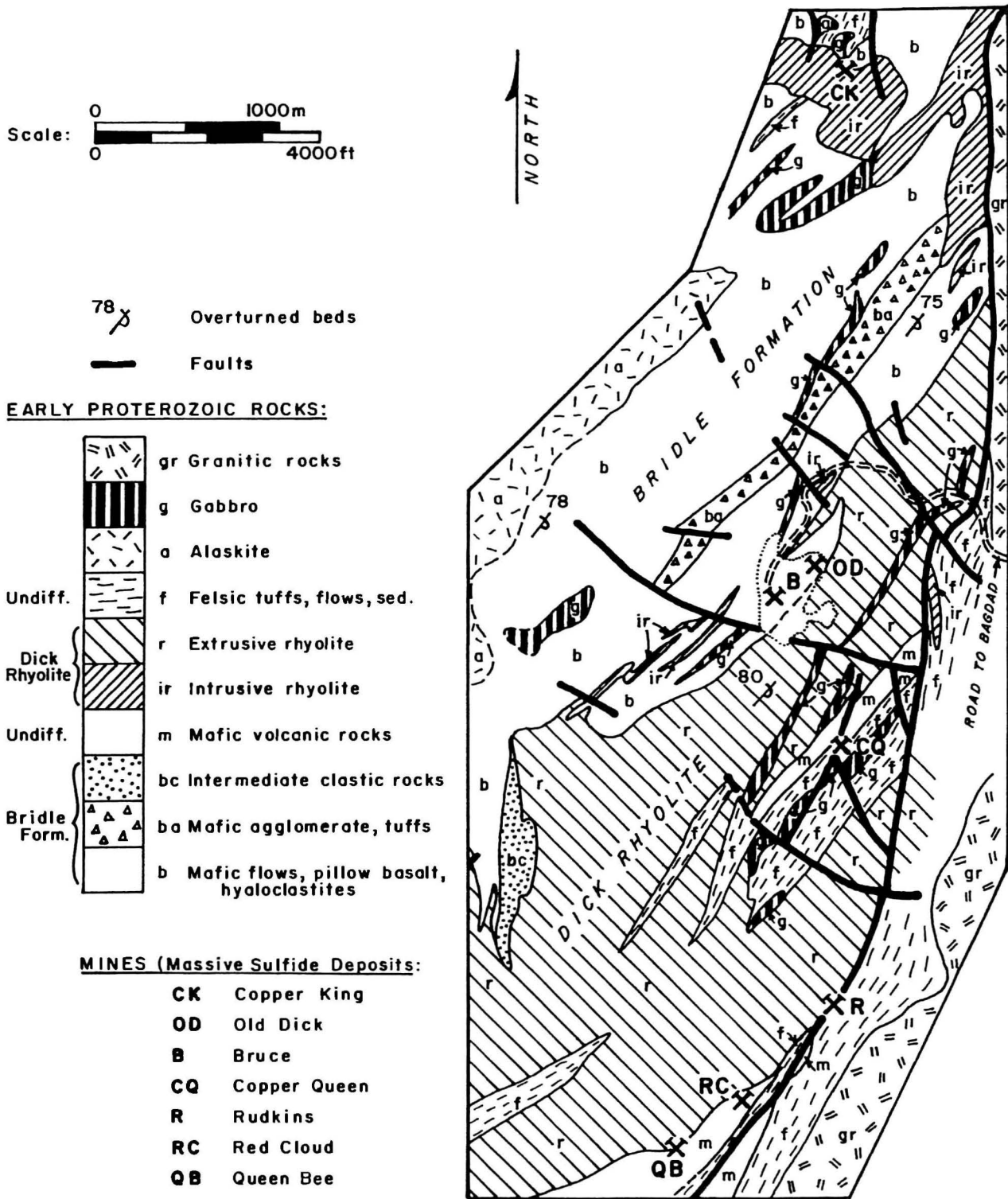RC   Red Cloud
QB   Queen Bee

Figure 10. Lithostratigraphic map of the Old Dick district, Bagdad, Arizona (modified from fig. 2 of Conway, Connelly, and Robison, 1986).
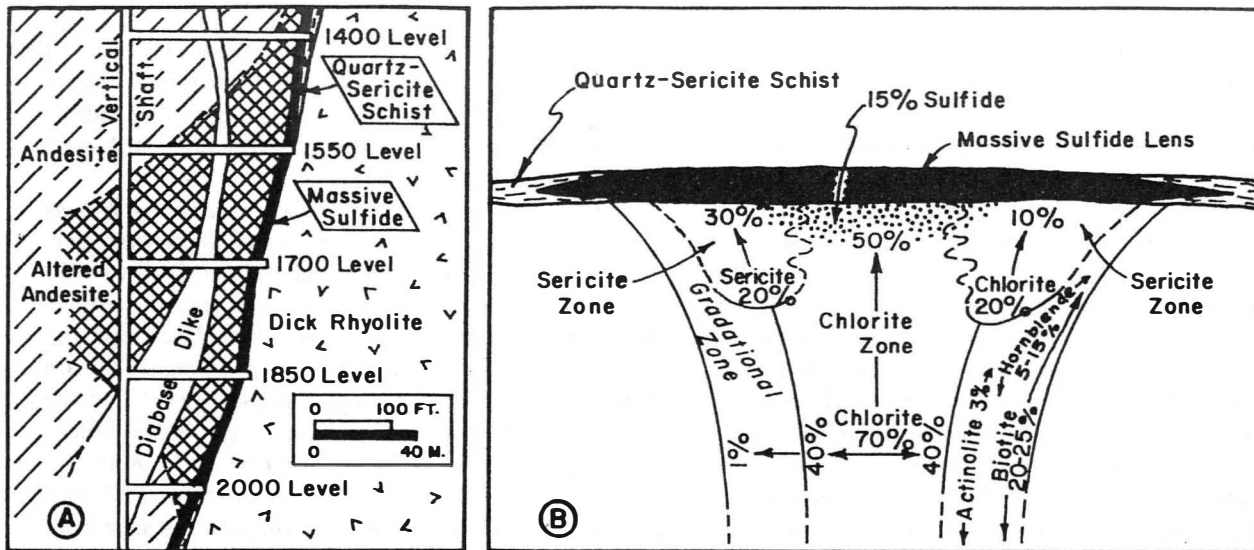
Figure 11. Real and reconstructed cross sections through the Bruce orebody, Bagdad, Arizona. A: Cross section through overturned Bruce mine orebody and alteration zone, facing northeast. The geology has been projected to a vertical plane that trends N. 55° W. and passes through the shaft. B: Schematic 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 quartzofeldspathic 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 $^{87}Rb/^{87}Sr$ 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.
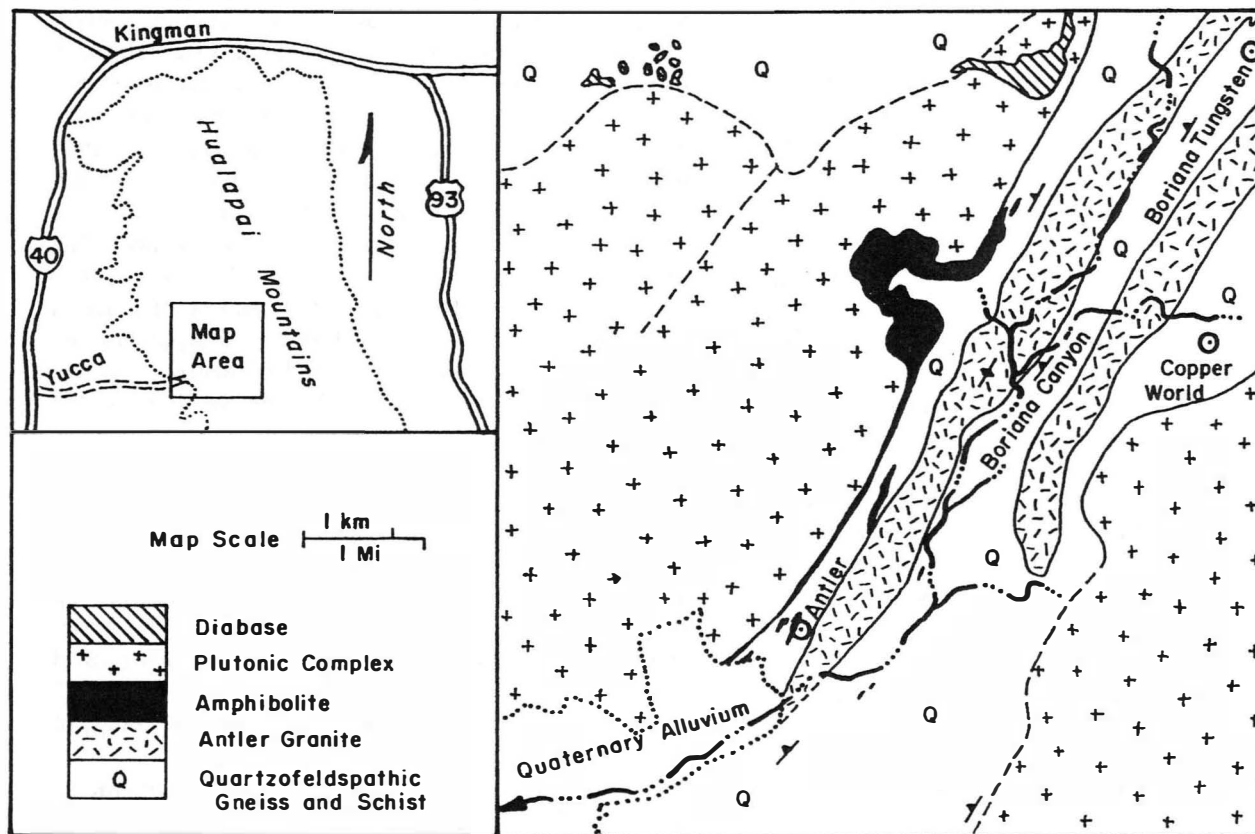

Figure 12. Regional geologic setting of the Antler and Copper World massive sulfide deposits, Hualapai district, Mohave County, Arizona. The conspicuous outcrop pattern in the amphibolite unit is known as the "Bulge." In the northeast corner of the map is the Tertiary Boriana tungsten deposit. The map 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 (± COPPER, ± LEAD, ± 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 (± GOLD, ± 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

MINERAL DEPOSITS HOSTED IN
LATER PROTEROZOIC ROCKS OF
GILA AND NAVAJO COUNTIES

■   HEMATITE DEPOSITS
    A-Apache
    B-Chediski

■   MAGNETITE DEPOSITS
    C-Center Mountain
    D-Zimmerman Point

⊕   URANIUM-PRODUCING AREA
    E-Bull Canyon Area
    F-Red Bluff Mine Area
    G-Workman Creek Area

⬯   ASBESTOS-PRODUCING AREA
    H- Southern Sierra Ancha
    I - Cherry Creek-Rock House
    J- Salt River-Chrysotile Area

(Source: Wrucke and others, 1986)

TUNGSTEN DISTRICTS

▲ Larger Producers:
   1-Camp Wood
   2-Tungstonia
   3-Aquarius Mountains
△ Smaller Producers:
   4-Garnet Mountain
   5-Fluorescent
   6-Ophir
   7-Three-in-one
   8-Lost
   9-Congress
   10-White Picacho
   11-Money Maker
   12-Camp Verde
   13-Four Peaks
   14-Wagner
   15-Whetstone

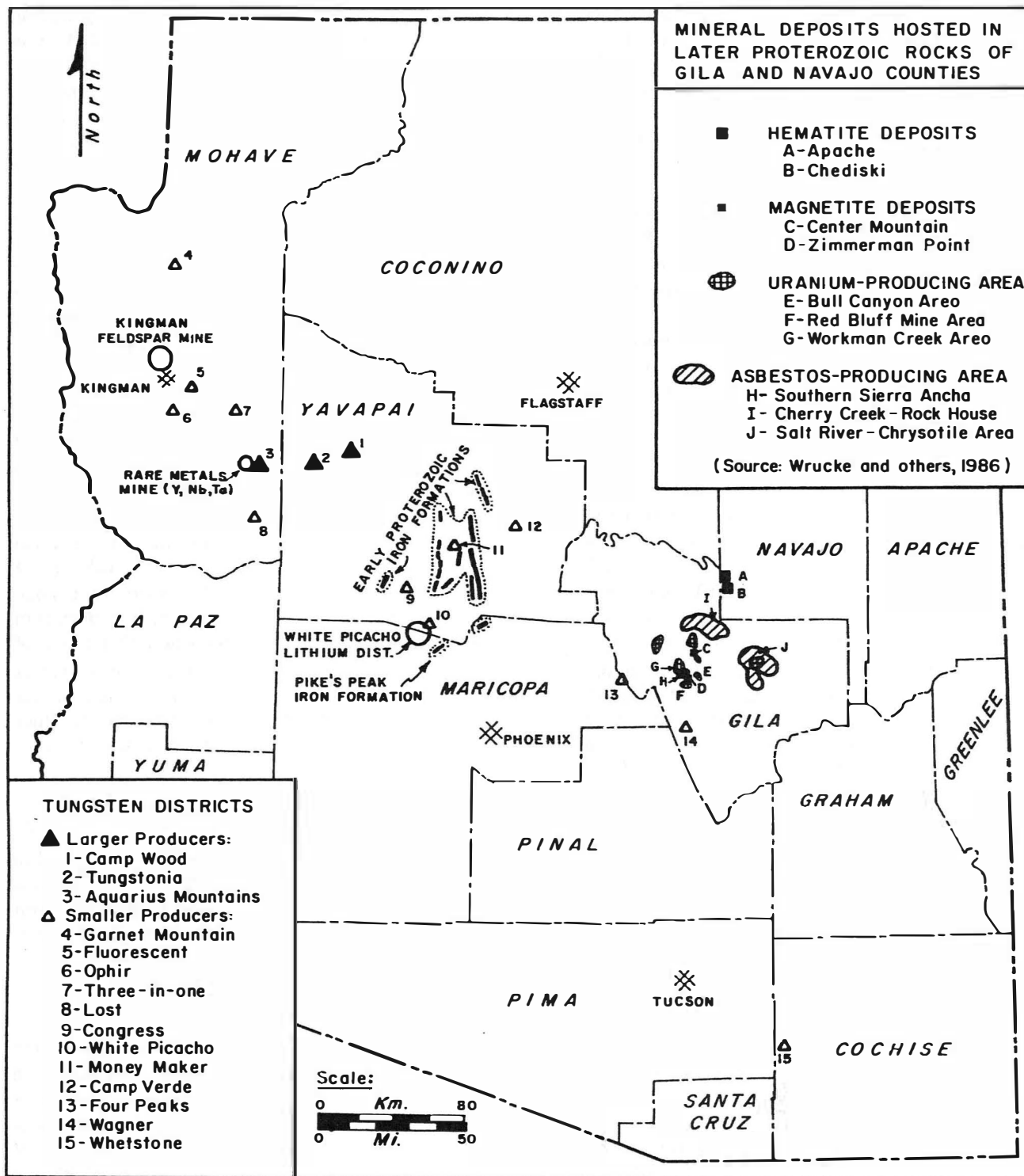Scale:
0   Km.   80
0   Mi.   50

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 Boriana 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 Boriana 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.

ACKNOWLEDGMENTS

The author is indebted to Dr. Spencer R. Titley of the University of Arizona at Tucson and Dr. Charles Meyer (deceased Nov. 15, 1987) of Sedona, Arizona, for their critical reviews and recommendations for improving the manuscript. Because of their attention to detail, the readability and meaning of the text have been improved. Thanks are also given to the Phelps Dodge Corporation, Verde Exploration Company, and CoCa Mines Inc., for supplying some of the material used in this compilation.

REFERENCES

Anderson, C. A., 1968, Arizona and adjacent New Mexico, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933-1967: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., v. II, p. 1164-1172.

Anderson, C. A., 1972, Precambrian rocks in the Cordes area, Yavapai County, Arizona: U.S. Geological Survey Bulletin 1345, p. 33-35.

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

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

Anderson, C. A., and Nash, J. T., 1972, Geology of the massive sulfide deposits at Jerome, Arizona—A re-interpretation: Economic Geology, v. 67, no. 7, p. 845-863.

Baker, A., 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: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., v. II, p. 1311-1327.

Cavalero, R. A., 1976, Geological map of the Skunk Canyon area, Bagdad, Arizona: Anaconda Minerals, unpublished map.

Chevillon, C. J., and Norris, J. R., 1986, Syngenetic gold mineralization in metamorphic rocks of the Mojave Desert region, California and Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 465.

Clayton, R. L., and Baker, A., 1973, Pb-Pb ages of a galena sample from the Bruce mine, Yavapai County, Arizona: Isochron/West, no. 6, p. 35.

Collins, D. E., 1977, Metamorphic geology of a portion of the Bagdad mining district, Yavapai County, Arizona: Reno, University of Nevada, unpublished M. S. thesis, 113 p.

Connelly, T. J., and Conway, C. M., 1983, Relation of Proterozoic massive sulfide deposits to contemporaneous volcanic activity, Bagdad, Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 298.

Conway, C. M., 1986, Field Guide to Early Proterozoic strata that host massive sulfide deposits at Bagdad, Arizona, *in* Nations, J. D., Conway, C. M., and Swann, G. A., eds., Geology of central and northern Arizona: Flagstaff, Arizona, Field trip guidebook for Geological Society of America Rocky Mountain Section Meeting, p. 140-157.

Conway, C. M., Connelly, T. J., and Robison, L. C., 1986, An Early Proterozoic volcanic-hydrothermal-exhalitive system at Bagdad, Arizona, *in* Beatty, Barbara, and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 24-34.

DeWitt, E., 1976, Precambrian geology and ore deposits of the Mayer-Crown King area, Yavapai County, Arizona: Tucson, University of Arizona, unpublished M. S. thesis, 150 p.

Donnelly, M. E., and Hahn, G. A., 1981, A review of the Precambrian volcanogenic massive sulfide deposits in central Arizona and their relationship to their depositional environment, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Tucson, Arizona Geological Society Digest 14, p. 11-21.

DeRosen-Spence, A., 1969, Gemese des roches a cordierite-anthophyllite des gisements cupro-zinciferes de la region de Rouyn-Noranda, Quebec, Canada: Canadian Journal of Earth Science, v. 6, p. 1339-1345.

Evenson, J. M., 1980, A structural interpretation of a portion of the Big Bug Group near Mayer, Arizona, *in* Jenney, J. P., and Stone, Claudia, eds., Studies in western Arizona: Tucson, Arizona Geological Society Digest 12, p. 167-176.

Forrester, J. D., 1963, Report on the Bobcat Mining Company property (Copper World mine) near Yucca, Mohave County, Arizona: Tucson, private report prepared for the University of Arizona.

Gilmour, P., 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: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, v. II, p. 1238-1257.

Guilbert, J. M., 1981, A plate tectonic-lithotectonic classification of ore deposits, *in* Dickinson, W. R., and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Tucson, Arizona Geological Society Digest 14, p. 1-10.

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, B., and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 339-342.

Gustin, M. S., 1987, Oral communication: University of Arizona.

Gustin, M. S., 1988, A petrological, geochemical, and stable isotope study of the alteration associated with the United Verde orebody, Jerome, Arizona: Tucson, University of Arizona, unpublished Ph.D. dissertation, 261 p.

Handverger, P. A., 1975, Geology and alteration of the United Verde Extension mine, Jerome, Arizona: American Institute of Mining, Metallurgical, and Petroleum Engineers, Preprint September, 1975, 26 p.

Harrer, C. M., 1964, Reconnaissance of iron resources in Arizona: U. S. Bureau of Mines Information Circular 8236, 204 p.

Heinrich, E. W., 1960, Some rare-earth mineral deposits in Mohave County, Arizona: Tucson, Arizona Bureau of Mines, Bulletin 167, 22 p.

Higgins, R.E., 1986, Geology of the Copper Queen mine, Mayer, Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers of geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 377-379.

Hobbs, S. W., 1969, Tungsten, *in* Mineral and water resources of Arizona: Tucson, Arizona Bureau of Mines, Bulletin 180, p. 276-281.

Hurlbut, D. F., 1986, The geology and mineralization at the Boggs mine, Yavapai County, Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 374-376.

Jahns, R. H., 1952, Pegmatite deposits of the White Picacho district, Maricopa and Yavapai Counties, Arizona: Tucson, Arizona Bureau of Mines, Bulletin 162, 105 p.

Karlstrom, K. E., and Conway, C. M., 1986, Deformational styles and contrasting lithostratigraphic sequences within an Early Proterozoic orogenic belt, central Arizona, *in* Nations, J. D., Conway, C. M., and Swann, G. A., eds., Geology of central and northern Arizona: Flagstaff, Northern Arizona University, Geological Society of America Field Trip Guidebook, p. 1-25.

Keith, S. B., Gest, D. E., DeWitt, E., Toll, N. W., and Everson, B. A., 1983, Metallic mineral districts and production in Arizona: Tucson, Arizona Bureau of Geology and Mineral Technology, Geological Survey Branch, Bulletin 194, 58 p.

Kessler, E. J., 1976, Rubidium-strontium geochronology and trace element geochemistry of Precambrian rocks in the northern Hualapai Mountains, Mohave County, Arizona: Tucson, University of Arizona, unpublished M. S. Thesis, 73 p.

Larson, P. B., 1976, The metamorphosed alteration zone associated with the Bruce Precambrian volcanogenic massive sulfide deposit, Yavapai County, Arizona: Tucson, University of Arizona, unpublished M. S. thesis, 99 p.

Larson, P. B., 1984, Geochemistry of the alteration pipe at the Bruce Cu-Zn volcanogenic massive sulfide deposit, Arizona: Economic Geology, v. 79, no. 8, p. 1880-1896.

Lavery, N. G., 1985, The use of fluorine as a pathfinder for volcanic-hosted massive sulfide ore deposits: Journal of Geochemical Exploration, no. 23, p. 35-60.

Lawrence, J. R., and Dixon, R. L., 1986, Geology of the Spud Mountain Tuff in the vicinity of the Iron King mine, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers of geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 370-373.

Lindberg, P. A., 1983, Development of the Verde graben, north central Arizona [abs.]: Flagstaff, Arizona, Arizona-Nevada Academy of Science, 27th Annual Meeting.

Lindberg, P. A., 1986a, An overview of Precambrian ore deposits of southwestern United States, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers of geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 18-23.

Lindberg, P. A., 1986b, Geology of the Copper Chief mine, Jerome district, Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 343-349.

Lindberg, P. A., 1986c, A brief geologic history and field guide to the Jerome district, Arizona, *in* Nations, J. D., Conway, C. H., and Swann, G. A., eds., Geology of central and northern Arizona: Flagstaff, Arizona, Field trip guidebook for Geological Society of America Rocky Mountain Section Meeting, p. 127-139.

Lindberg, P. A., and Jacobson, H. S., 1974, Economic geology and field guide of the Jerome District, Arizona, *in* Geology of Northern Arizona, Part II, Area studies and field guides: Flagstaff, Arizona, Geological Society of America Rocky Mountain Section Meeting, p. 794-804.

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

London, D., and Burt, D. M., 1978, Lithium pegmatites of the White Picacho district, Maricopa and Yavapai Counties, Arizona, *in* Burt, D. M., and Pewe, T. L., eds., Guidebook to the geology of central Arizona: Tucson, State of Arizona Bureau of Geology and Mineral Technology, Special Paper no. 2, p. 60-72.

Lundin, R. L., 1985, The Zonia mine area: Prescott, Arizona, Field guide for Central Arizona Geological Society, 8 p.

McKee, E. H., and Anderson, C. A., 1971, Age and chemistry of Tertiary volcanic rocks in north-central Arizona and their relationship to the Colorado Plateaus: Geological Society of America Bulletin, v. 82, p. 2767-2782.

Meyer, C., 1972, Private company reports and mapping, Jerome, Arizona.

Nutt, C. J., 1984, Strata-bound uranium deposits in the Dripping Spring Quartzite, Gila County, Arizona, U.S.A., *in* Ferguson, J., ed., Proterozoic unconformity and stratabound uranium deposits: Report of the working group on uranium geology organized by the International Atomic Energy Agency TECDOC-315, p. 95-113.

O'Hara, P. F., 1986a, Previous geologic work in the Prescott-Mayer area, Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers of geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 355-357.

O'Hara, P. F., 1986b, Stratigraphy and structural geology in the Prescott-Mayer area, Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers of geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 358-364.

Otton, J. K., Light, T. D., Shride, A. F., Bergquist, J. R., Wrucke, C. T., Theobald, P. K., Duval, J. S., and Wilson, D. M., 1981, Mineral resources of the Sierra Ancha Wilderness and Salome Study Area, Gila County, Arizona: Summary report, U. S. Geological Survey Miscellaneous Field Investigations Map MF-1162-H, 6 p.

Ransome, F. L., 1933, General geology and summary of ore deposits, *in* Ore deposits of the Southwest: Washington, D. C., 16th International Geologic Congress Guidebook 14, Excursion C-1, p. 1-23.

Sangster, D. F., 1972, Precambrian volcanogenic massive sulfide deposits in Canada; a review: Geological Survey of Canada, Paper 72-22, 44 p.

Shride, A. F., 1967, Younger Precambrian geology in southern Arizona: U. S. Geological Survey Professional Paper 566, 89 p.

Slatt, R. M., Heintz, G. M., Lowry, P. H., and O'Hara, P. F., 1978, Precambrian Pike's Peak iron-formation, central Arizona, *in* Burt, D. M., and Pewe, T. L., eds., Guidebook to the geology of central Arizona: Tucson, State of Arizona Bureau of Geology and Mineral Technology, Special Paper No. 2, p. 73-82.

Stan West Mining Corporation, 1983, Annual Report: Phoenix, Arizona, 18 p.

Stensrud, H. L., and More, S., 1980, Precambrian geology and massive sulfide environments of the west-central Hualapai Mountains, Mohave County—A preliminary report, *in* Jenney, J. P., and Stone, C., eds., Studies in western Arizona: Tucson, Arizona Geological Society Digest 12, p. 155-165.

Still, A. R., 1974, Review of geology and recommendations for exploration, Antler mine and adjacent areas, Mohave County, Arizona: Tucson, private report prepared for Standard Metals Corp., 32 p.

Swan, M. M., Hausen, D. M., and Newell, R. A., 1982, Lithological, structural, chemical, and mineralogical patterns in a Precambrian stratiform gold occurrence, Yavapai County, Arizona, *in* Hausen, D. M., and Parks, W. C., eds., Process metallurgy: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 143-157.

Welty, J. W., Reynolds, S. J., Keith, S. B., Gest, D. E., Trapp, R. A., and DeWitt, E., 1985, Mine index for metallic mineral districts of Arizona: Tucson, Arizona Bureau of Geology and Mineral Technology Bulletin 196, 92 p.

White, D., 1986, Gold distribution at the United Verde Extension, a massive base-metal sulfide deposit, Jerome, Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 330-338.

Wrucke, C. T., Otton, J. K., and Desborough, G. A., 1986, Summary and origin of the mineral commodities in the Middle Proterozoic Apache Group in central Arizona, *in* Beatty, B., and Wilkinson, P. A. K., eds., Frontiers in geology and ore deposits of Arizona and the Southwest: Tucson, Arizona Geological Society Digest 16, p. 12-17.

SUBOXIC DEEP SEAWATER AT CA. 1.74 GA: EVIDENCE FROM SEAFLOOR-HYDROTHERMAL JASPER AND IRON-FORMATION IN THE JEROME DISTRICT, ARIZONA

SLACK, John F., U.S. Geol Survey, National Center, MS 954, Reston, VA 20192, jfslack@usgs.gov, GRENNE, Tor, Geol Survey of Norway, Leiv Eirikssons vei 39, Trondheim, 7491, Norway, BEKKER, Andrey, Geophysical Lab, Carnegie Institution of Washington, 5251 Broad Branch Road, Washington, DC 20015, ROUXEL, Olivier J., Dept Marine Chemistry and Geochemistry, Woods Hole Oceanographic Institution, MS 8, Woods Hole, MA 02543, and LINDBERG, Paul A., 205 Paramount Dr, Sedona, AZ 86336-6609

Fine-grained quartz-hematite rock (jasper) in the Jerome district forms bedded units <1 m thick below, within, and above rhyolite tuff of the ca. 1.74 Ga Cleopatra Rhyolite. Interlayered jasper and hematite-facies iron-formation up to 3 m thick occur in overlying turbidites of the Grapevine Gulch Formation. The rhyolite-hosted jasper beds are both proximal and distal to Cu-rich volcanogenic massive sulfide (VMS) deposits at the Jerome and Copper Chief mines. Hematitic filaments 1-3 µm in diameter and 30-50 µm long in some jasper are morphologically similar to remains of iron-oxidizing bacteria in Ordovician and younger VMS-related jasper. Water depth during mineralization was >1500 m as constrained by inferred temperatures of ≥350°C in non-boiling vent fluids, which were needed to carry appreciable Cu in solution to form the seafloor VMS deposits. Whole-rock analyses of the jasper and iron-formation show low MnO concentrations (<0.1 wt %) and REE patterns with generally small negative Eu anomalies and no or small positive Ce anomalies (Ce/Ce* up to 1.48). Analogy with REE systematics in modern stratified water columns suggests that the positive Ce anomalies developed by redox cycling at an oxic-suboxic boundary. The resultant positive Ce anomalies formed in underlying suboxic waters through scavenging of Ce(III) by ferric oxyhydroxide particles that precipited in VMS-related hydrothermal plumes.

A recent model for Proterozoic seawater chemistry (Poulton et al., 2004) involves a fundamental change at 1.8 Ga when previously anoxic deep ocean waters evolved to euxinic (sulfidic) conditions with this redox state continuing until about 1.0 Ga when the deep oceans became dominantly oxic. Occurrence in the Jerome district of abundant primary ferric iron in jasper and iron-formation, together with remains of Fe-oxidizing bacteria, imply suboxic conditions in the deep ocean at ca. 1.74 Ga. The redox state of deep seawater in the Jerome region was above that required for Fe-oxidation but below the redox states of Ce- and Mn-oxidation. Our data suggest a significant lag in oxidation of the deep oceans after the rise of atmospheric oxygen at ca. 2.3 Ga, and raise the possibility that 1.8-1.0 Ga deep seawater was neither euxinic nor fully oxygenated.