Precambrian Geology and Massive Sulfide Environments of the West-Central Hualapai Mountains, Mohave County, Arizona — A Preliminary Report

by

Howard L. Stensrud[1] and Syver More[2]

Abstract

The older Precambrian rocks (near 1.8 b.y.) of the west-central Hualapai Mountains, Arizona, consist of intermediate to felsic schists, gneisses, and amphibolites, primarily derived from volcanic, volcaniclastic, and sedimentary rocks that have undergone amphibolite-facies regional metamorphism. At least two deformational events are evident, but the structure is dominated by a strong N. 30° E. regional foliation trend with a later, subsidiary, north-northwest shear component. The metamorphic rocks have been cut by numerous quasi-conformable Precambrian granitic plutons and later Precambrian pegmatites and diabases. Vein tungsten deposits of the Boriana mine appear to be related to a southwest-trending Precambrian granitic prong. A granite-bounded northeast-trending belt of metamorphic rocks (2 km wide), with bulbous to layered amphibolites, felsic gneisses, and pelitic schists, contains two thin, stratiform massive sulfide deposits of interest: at the Antler mine and the Copper World mine. Both deposits contain the sulfide assemblage pyrite, pyrrhotite, chalcopyrite, sphalerite, and rare galena. Cordierite and anthopyllite are present in the associated silicate assemblage. At the Antler mine the high degree of deformation, with translation and folding complicated by thermal overprinting, has resulted in a complex, narrow, north-plunging orebody. The Copper World deposit may exhibit similar geometry on a reduced scale. These deposits probably are of proximal-facies volcanogenic origin; definite recognition will require an extensive reconstruction of the surrounding terrain.

Introduction

The Hualapai Mountains of northwestern Arizona are a Precambrian plutonic-metamorphic complex, uplifted in basin-range time, which is capped at the north end by a veneer of Tertiary and Quaternary volcanic rocks, and in places is invaded by small Cretaceous or Tertiary intrusive bodies (Wilson and Moore, 1959). Most Precambrian rocks in the Hualapai Mountains are presumed to be middle Proterozoic in age, often called "older Precambrian" to contrast them with the younger, late Precambrian rocks such as those in the Grand Canyon supergroup (Ford and Breed, 1976). Tabular mafic intrusions in the Hualapais may be late Precambrian or younger.

The area of this study encompasses about 150 square kilometers, with principal access via Yucca, Arizona, by the road that passes near the Antler, Copper World, and Boriana mines (Fig. 1). This report should be viewed as a preliminary status report; some parts of the area have been mapped in detail, others only in reconnaissance fashion. Uncertainties remain; nevertheless, we view this as a necessary step to the many man-years of field work that remain before a complete, coherent picture of the geology of the Hualapai Mountains emerges.

Previous Work

Published and unpublished but accessible data concerning the Precambrian geology of the Hualapai Mountains are scarce. The county geologic map (Wilson and Moore, 1959) shows the gross distribution of some major rock units. Two unpublished M.S. theses from the University of Arizona treat aspects of the geology (Vuich, 1974) and isotope geochemistry (Kessler, 1976) of the northernmost Hualapai

[1]California State University, Chico, California 95929.

[2]University of Arizona, Tucson, Arizona 85721.

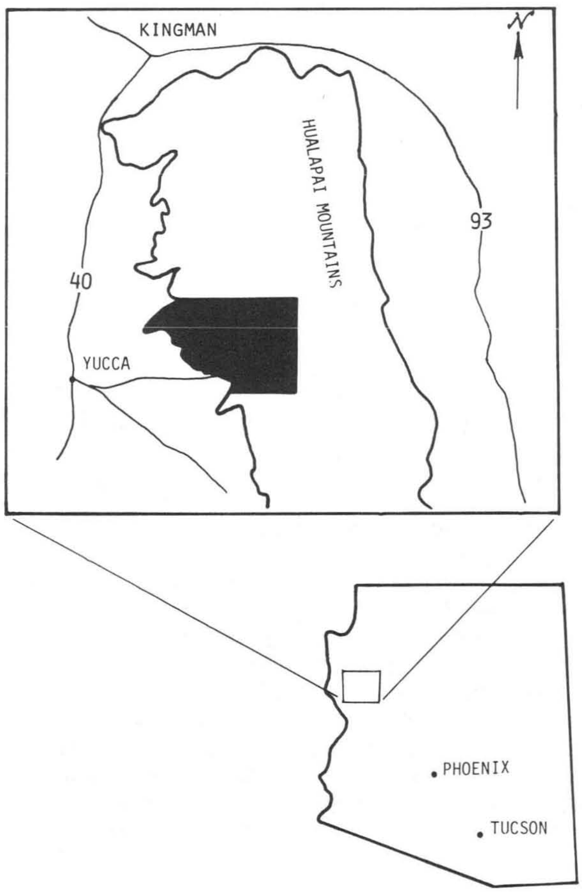

Fig. 1. Location map, west-central Hualapai Mountains

Mountains. A current doctoral study by Phillip Anderson includes some general aspects of the Precambrian geology of the Hualapai Mountains as part of a regional Precambrian study.

Within the area treated by this study only four relatively modern published reports exist: Hobbs (1944) on the Boriana mine, Rasor (1946) on a mineral occurrence in the Copper World mine, Romslo (1948) on the Antler mine, and Putnam and Burnham (1963) on some of the batholithic rocks. The geochemical study by Putnam and Burnham (1963) includes trace and major element analyses of some plutonic rocks of the Hualapai Mountains. Regrettably, their work did not include a geologic map and sample localities were not adequately described, thus limiting the usefulness of their data.

Metamorphic Rocks

Amphibolites

Tabular and bulbous bodies of fine- to coarse-grained, often porphyroblastic amphibolite crop out extensively on the northwest side of Boriana Canyon, mainly west of the prong of Antler granite (Fig. 2). The largest amphibolite mass, located 4 km north-northeast of the Antler mine is known locally as the "Bulge." Lesser occurrences of amphibolite can be found in the vicinity of the Antler mine and as isolated but similar-trending tabular bodies at the western margin of the Precambrian outcrops. Although no attempt was made to subdivide amphibolite units on the map (Fig. 2), textural and mineralogical variations are obvious. Complete details may be found in More (1980).

In Boriana Canyon two amphibolite subtypes can be recognized: a hornblende-dominant amphibolite and a quartz–hornblende–feldspar amphibolite. The hornblende-dominant subtype is dark gray to black in outcrop and is especially common at the Bulge where units attain apparent thicknesses of 250 to 600 m. Elsewhere these dark amphibolites are 5 to 60 m thick. Coarse and fine-grained textural varieties dominate, but some amphibolites are strikingly porphyroblastic, giving a distinct spotted appearance to the outcrop. In such rocks, 0.5 to 2 cm elongate porphyroblasts of green hornblende occur in a foliated matrix of finer grained (0.2-3 mm) hornblende and plagioclase (An_{50}-An_{66}). Textural variations among amphibolites may be abrupt and striking in the field such that two or more textural variants may be adjacent within one outcrop.

Pale-green diopsidic augite occurs as an important major phase in some amphibolites within Boriana Canyon, but it is absent in other amphibolite units. The clinopyroxene, where present, is subordinate in amount to the hornblende. Plagioclase and lesser quartz make up the felsic assemblage in the hornblende-dominant amphibolites, usually in amounts about equal to the hornblende or hornblende plus pyroxene. In the Bulge, garnet porphyroblasts are found rimmed with hornblende and plagioclase, producing an augenlike texture. Observed accessory minerals include sphene, apatite, zircon, elongate opaques, and epidote.

The quartz–hornblende–plagioclase variety of amphibolite tends to be fine to medium grained and medium to light gray in outcrop due to lesser amounts of hornblende (<33%) and an increasing felsic proportion. This variety may grade into or become intercalcated with the hornblende-dominant variety. Mineralogic constituents include plagioclase (An_{25}-An_{45}), quartz, and hornblende, with minor

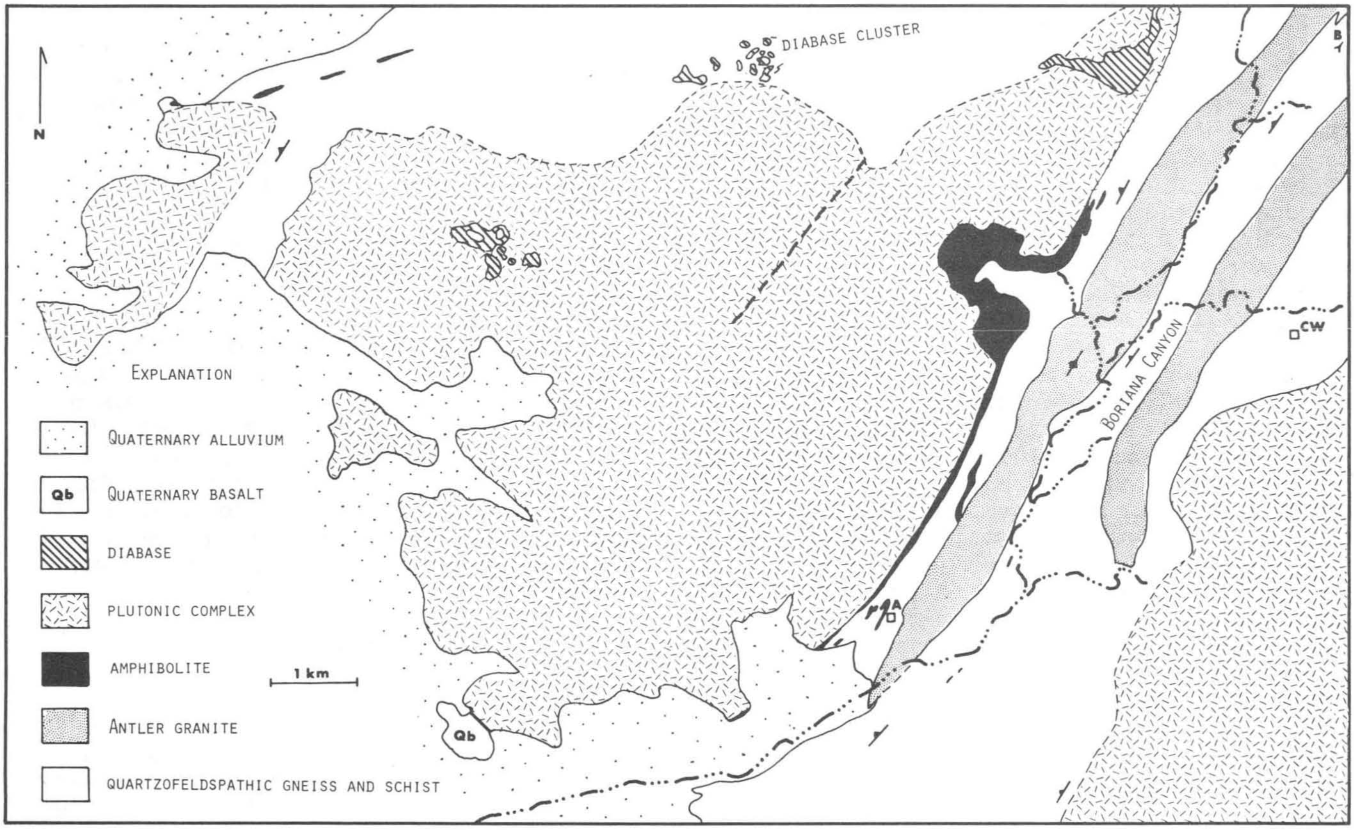

Fig. 2. Generalized geologic map of the west-central Hualapai Mountains

opaques, epidote, potassium feldspar, ± biotite ± clinopyroxene.

Quartzofeldspathic Rocks

Gneisses, schists, and phyllites of variable mineralogy make up the bulk of the non-plutonic rocks in the west-central Hualapai Mountains. Amphibolites are the only other mappable metamorphic rock type of areal significance. Subdivision into specific types is not possible at the map scale of Figure 2; however, a more detailed larger scale map of the Boriana Canyon metamorphic belt is available in More (1980). In this section we will generally describe some of the more important mineralogic and textural variants observed and draw attention to their major outcrop areas.

The Boriana Canyon metamorphic belt (Fig. 2) includes the greatest variety of metamorphic rocks. As a generalization, the quartzofeldspathic rocks may be divided into two groups, which are field discernible: (1) quartz-mica rocks in which muscovite is more abundant than biotite and (2) quartz-biotite-dominant rocks in which biotite exceeds muscovite. These two units are roughly divided by the wedge of Antler granite (Fig. 2) such that quartz-mica rocks dominate east of the granite screen and quartz-biotite rocks dominate west of the granite screen.

Quartz–Mica Rocks

Quartz–mica rocks constitute the largest percentage of outcrop among metamorphic rocks in Boriana Canyon, but they are rare elsewhere in the study area. They are typically very fine to fine grained, light greenish gray to gray, phyllitic or schistose micaceous rocks, which are dominated by the assemblage quartz + muscovite ± biotite ± chlorite. The percentage of quartz averages about 50, with a range from 20 to 80. Muscovite content ranges from 5 to 40 percent. Minor potassium feldspar is present and almandine garnet, though not abundant, is common in a few thin siliceous zones.

East of the Antler granite the quartz–mica units are folded and cut by numerous pegmatites, largely conformable, but some cross cutting. Within this sequence are thin 20-60 cm biotite-dominant schist sections intercalated among muscovite-rich schist. Several of these exposed sections reveal "graded bedding," but the changes induced by metamorphism, the structure, and the uncertainty of the textural character of the protolith make top and bottom determinations ambiguous across the folded terrain.

Other, less ambiguous primary features can be recognized within this zone, however. About 1,300 m east of the Antler mine a well-preserved but small conglomerate unit is located. Rounded clasts, up to 15 cm across, of quartz-biotite rock occur in a fine-grained schistose matrix. Some unusual spotted schists are found near the Boriana mine and southward. Elongate white spots, 2-4 cm across on the foliation surface, occur within a matrix of very fine grained gray schist. The spots are lensoidal in cross section and must represent flattened and stretched clasts. Petrographically, the white spots consist of very fine grained muscovite and quartz, whereas the surrounding gray schist has abundant biotite as well.

Near the southeast margin of the Boriana metamorphic belt large (2-8 cm), elongate, dark-gray, sieved porphyroblasts of andalusite occur, typically lying in a contorted foliation plane. Minor staurolite occurs with the andalusite. To the northeast in the phyllitic rocks east of the Boriana mine, near the contact with a pluton, andalusite also occurs but in spotted phyllites, which show optically continuous relicts of andalusite engulfed by clusters of muscovite. These muscovite–andalusite spots are within weakly foliated, fine-grained aggregates of muscovite, biotite, quartz, and feldspar.

Quartz–Biotite Rocks

Quartz–biotite gneisses and schists find their thickest expression west of the Antler granite (Fig. 2). Very fine to fine-grained, buff-tan to medium greenish-gray felsic rocks with blocky habit attain apparent thicknesses of 15-20 m near the Antler workings, thickening northward to as much as 290 m on the Bulge. "Ghost" fragmental textures can be recognized in some outcrops, although original clasts have been thoroughly stretched, flattened, and metamorphosed. In drill core samples a pseudofragmental unit can be seen, which displays elongated lenses and fold hinges of slightly more felsic nature, which may reflect structural disruption rather than remnant clasts.

In detail the quartz–biotite-dominant rocks occur in two variants that show both textural and mineralogic differences.

1. The more abundant variant typically contains about 45% quartz, 40% microcline, 1-15% albitic plagioclase, 5-10% brown biotite, and minor amounts of garnet, apatite, and magnetite. This forms the principal host rock for the copper-zinc ores at the Antler and Copper World mines. Small (0.1-2 mm) sillimanite needles occur in this unit near the contact with muscovite granite near the Copper World mine.

2. The second type of quartz–biotite rock is quartz dominant, with quartz nearly 60 percent of the high potassium feldspar rocks and increasing to 80 percent in the low potassium feldspar rocks. Orthoclase (10-15%) is the dominant potassium feldspar type, with albitic plagioclase up to 10 percent, biotite about 12 percent, muscovite typically 2-5 percent. Minor constituents include traces of garnet, hornblende, and rare phlogopite.

Intrusive Rocks

Western Hualapai Plutonic Complex

An elongate plutonic igneous complex of batholithic dimensions crops out almost continuously for 80 km on the western margin of the Hualapai Mountains. Satellitic plutons may extend this distance considerably. For convenience this complex will be called the western Hualapai plutonic complex. The complex, as exposed in the study area, appears to consist of at least three field-discernible phases, each of which has distinctive textural and (or) mineralogic characteristics: (1) a fine-grained intermediate phase, (2) a coarsely porphyritic phase, and (3) a texturally homogeneous, weakly foliated phase. Field relations show that the porphyritic phase cuts the intermediate phase; the relative position of the homogeneous phase is uncertain, but it is probably the oldest unit.

The intermediate phase crops out southeast of Boriana Canyon only and consists of a fine- to medium-grained granodiorite with 50-60% plagioclase (An_{32} to An_{42}), 10-20% quartz, 10-20% brown biotite, 10-15% microcline, and about 5% green hornblende. Accessory minerals include ilmenite, sphene, zircon, allanite, and apatite. Rare phenocrysts of plagioclase, 1 to 2 cm, are scattered throughout. Myrmekite and perthite are common. There is no petrographic evidence for a penetrative metamorphic fabric, but deformation twinning of plagioclase and undulose extinction of quartz are observed.

The porphyritic phase also crops out only southeast of Boriana. It is believed to be a quartz monzonite, but because of the coarseness of grain size it is difficult to obtain statistically valid modes from thin sections. Individual thin sections show compositional ranges from true granite to granodiorite. Most fall into the quartz monzonite range, however. The rock consists of 60-70% feldspar, mainly as 1-3 cm phenocrysts of perthitic potassium feldspar and plaid-twinned microcline plus somewhat smaller (1-2 cm) phenocrysts of plagioclase (An_{26}-An_{34}). Medium-grained quartz (10-20%) and pale-brown biotite (5-15%) are the other major phases. Accessory minerals include zircon, allanite, apatite, ilmenite, and in one sample, several percent fluorite. Patchy and erratic phenocryst alignments within this phase appear to represent localized primary flowage phenomena rather than a post-crystallization feature.

The weakly foliated, texturally homogeneous phase crops out primarily northwest of Boriana Canyon. It is medium grained, lacks obvious phenocrysts, and compositionally is a granodiorite. Plagioclase (An_{26}-An_{34}), often untwinned, is always the dominant feldspar; potassium feldspar, as either perthite or microcline, ranges from 5 to 25% and is often interstitial. Quartz (10-20%) and greenish-brown biotite (3-10%) are the remaining major phases. Accessory minerals include sphene, zircon, apatite, and opaques. Traces of chlorite and muscovite occur in some altered samples.

Intraplutonic pegmatite bodies are common and mineralogically simple; generally they contain quartz and feldspars only, although some contain small (1 cm) garnets.

Contacts between plutonic phases and other rock units are often sharp, essentially knife-edge or definable within a few meters. A major exception occurs on the southeast margin of Boriana Canyon where in places a zone of injection migmatite of varying thickness intervenes between the pluton and adjacent metasediments. This migmatitic zone is characterized by narrow lit-par-lit injections and bulbous dikes of granitic and pegmatitic material, which have been intruded along foliation planes. Leucogranitic dikes widen to thick (50+ m) zones with thin partitions of quartz-mica schist within them. These schistose partitions are typically sillimanite bearing. We perceive this zone to be an injection migmatite as defined by Winkler (1976, p. 278).

Antler Granite

Two well-foliated, northeast-trending, narrow bodies of muscovite-biotite granite extend into the Boriana Canyon metamorphic belt from the northeast. The larger body terminates near the Antler mine (Fig. 2), and for convenience we will hereafter refer to this granitic unit as the Antler granite. It is a true granite, slightly porphyritic, generally medium to coarse grained, consisting of 30-40% potassium feldspar (as microcline and perthite), 20-30% quartz, 10-20% plagioclase (An_{26}-An_{32}), 10-15% brown biotite, and about 5% muscovite. Pleochroic halos are common in the biotites. Accessory minerals include zircon, opaques, and apatite.

Xenoliths of micaceous rocks similar to nearby wall rock are common, muscovite-rich to the north, biotite-rich toward the Antler mine. Field relations for these granitic bodies are not totally clear. Although contacts in many places are abrupt and obvious, the margins of the smaller body (Fig. 2) are obscured to the north and east against a migmatitic zone, and it is bluntly terminated to the south--possibly fault truncated. The main granite body continues to the northeast past the Boriana mine, but its exact extent is unknown.

Pegmatites

Pegmatite bodies are abundant throughout the area studied but particularly so in the Boriana Canyon metamorphic belt. The pegmatites cut all exposed Precambrian rocks except the diabase. Most are conformable, with thicknesses from a few centimeters to over 60 m and lengths to over 200 m. Other pegmatites, however, are crosscutting, irregularly shaped, bulbous and podiform bodies with long dimensions rarely exceeding a few tens of meters. Mineralogically, most pegmatites are simple, consisting of quartz, pink to white potassium feldspar, white to gray sodic plagioclase, and minor muscovite. Near the migmatite zone on the east side of Boriana Canyon are a few thin, concordant pegmatites containing abundant black tourmaline up to 10 cm long elongated normal to the wall-rock contact. Garnets up to 1 cm were observed in some intraplutonic pegmatites.

Samples of pegmatite float from Boriana Canyon show pervasive epidotization of plagioclase with blue fluorite deposited in fractures. No similarly altered and mineralized pegmatites were seen in place, however.

Diabase

Tabular bodies of diabase, from a few meters to tens of meters thick, crop out in four separate localities within the study area. Present orientations are mostly subhorizontal to gently dipping. The largest outcrop is a north-facing dip slope, roughly triangular in plan view, that comprises about 0.5 km^2 of surface area (Fig. 2). Other localities, much smaller in surface area, are about 3 km west, 6 km west, and 11 km south of the largest mass. The smaller occurrences often consist of several individual diabase bodies, but some are possibly a larger body fragmented by faulting.

In outcrop the diabases are dark gray to black and display a distinctive reddish-brown, mottled weathering surface. In thin section the diabases show considerable mineralogic variability. The essential phases include plagioclase (An_{50}-An_{64}), typically as well-formed 1-2 mm laths, and augite, usually as pale-brown ophitic plates. Olivine is often present (up to 20%), hypersthene occurs as a subordinate pyroxene in some samples, and opaque oxides are ubiquitous, sometimes rimmed by minor reddish-brown biotite. The observed variations may reflect genuine differences in the primary mineralogy between entire diabase bodies or possibly may reflect internal variations between heterogeneous diabase bodies. No attempt was made to systematically identify such internal variations.

Field relations do not define the age of the diabase except that only Precambrian rocks are cut by the diabase and the diabase, in turn, is not intruded by any Precambrian rocks. Similar diabase bodies are widely known throughout the Precambrian of Arizona. Vuich (1974) reported numerous diabase bodies in the northeastern Hualapai Mountains. Allan and Swan (1978) referred to a 1.1 b.y. old diabase emplacement event of regional scale in the southwestern United States. The observed diabase bodies may be representatives of that event in total or in part, or they may be much younger, but convincing support awaits radiometric dating.

Metamorphism

The details of the metamorphic history in the west-central Hualapai Mountains are presently unclear, and in light of existing data, enigmatic. Excluding major plutons, it is clear that the entire area studied has been subjected to at least one episode of medium- to high-grade regional metamorphism as indicated by the pervasive foliation and the presence of diagnostic mineral assemblages. Late thermal overprinting and retrograde metamorphism are superimposed upon the regional pattern.

The Boriana Canyon metamorphic belt contains abundant foliated amphibolites with the assemblage hornblende + diopsidic augite + plagioclase. Near the Antler mine some amphibolites contain retrograde epidote. West of Boriana Canyon, however, the amphibolites are pyroxene free and some contain apparent prograde epidote. Thus, the Boriana Canyon metamorphic belt must represent a generally higher metamorphic grade than areas several kilometers to the west, that is, high amphibolite facies versus lower amphibolite facies.

The presence of andalusite in pelitic rocks on the southeast side of the Boriana Canyon metamorphic belt is significant. East of the Antler mine are large (up to 5 cm) andalusite porphyroblasts, which coexist with biotite and minor staurolite. East of the Boriana mine are pelitic schists, which contain relict andalusite masses within clusters of muscovite. These andalusite occurrences presumably indicate a late, relatively low pressure thermal and hydrothermal event with the nearby pluton(s) to the southeast as a likely heat source.

Other thermally induced metamorphic effects are the fibrous silicate assemblages associated with the Antler sulfide body (e.g., cordierite–anthophyllite–biotite) as well as textural and mineralogical changes evident within the massive sulfide deposit itself.

The sulfide assemblage present in the Antler mine, pyrite–pyrrhotite–sphalerite, has been shown by Scott (1976) to be of values in evaluating metamorphic pressure--the sphalerite geobarometer. Microprobe analyses were performed on sphalerites in mutual contact with pyrite and pyrrhotite from sulfide core samples taken from Antler mine drill holes B2, B5, and B7. Calculated pressure values based on the mole percent FeS, using the graph from Scott (1976), are 5 kb, 5 kb, and 7 kb for the three samples, respectively. The disagreement between the three values is puzzling, but at this time we are not prepared to explain these variations. Regardless, the pressure values indicated by the sphalerite geobarometer seem to be too high. Consideration of the various assemblages present throughout the Boriana Canyon area would seem in light of the data from Winkler (1976) to place the general temperatures of metamorphism in the range of 450°-565°C and pressures from 1 to 4 kb.

Structure

The metamorphic rocks in the west-central Hualapai Mountains show a strong N. 30°-40° E. foliation trend typically with high dip angles, although local deviations from this trend occur, notably within amphibolites on the Bulge. The foliation generally reflects strong isoclinal folding by passive slip deformation. Two such Precambrian deformation events are widely recognized in northwestern Arizona, whereas other parts of the state show only one event (Phillip Anderson, pers. comm., 1979).

At least two generations of folds are present in Boriana Canyon. The first phase is difficult to discern but is indicated by rare remnants of an earlier foliation at a slight angle to the present foliation. The second phase of folding resulted in transposition and the development of dominantly southwest-plunging, tight-to isoclinal folds, with less common north-plunging structures at the Antler and Copper World deposits. Some individual isoclinal folds can be recognized in Boriana Canyon but rarely elsewhere because of poor exposure or inappropriate lithologies for recognition of repeated fold limbs. Occasional angular discordance between lithologic contacts and foliation indicates that present foliation does not necessarily reflect original compositional layering.

A strong northwest-trending shear set cuts most of the area. This trend is most evident as photolinears readily seen in both low- and high-altitude photography. The photolinears are subparallel but occasionally converge. Typically, they have a spacing interval of about 150 to 300 m. On the ground the linear features are not readily evident but are indicated by thin, often chloritized or siliceous brecciated zones and small-scale apparent left-lateral offsets (up to 30 m). Vertical offsets are also likely, but amount of displacement is conjectural.

Younger faults, with dominantly vertical displacements, are present within the area, but amount of offset is difficult to demonstrate. Striking linear northeast-trending valleys in the batholithic rocks, with apparent topographic discord rim to rim, give compelling support for the existence of such faults, but direct surface evidence is lacking, in part because they are obscured by parallelism to the foliation. A linear contact between batholithic rocks and a small patch of Tertiary-Quaternary basalt at the same elevation about 5 km due west of the Antler mine must be a fault contact.

Economic Geology

Three mineral deposits with a history of modern production are found in the west-central Hualapai Mountains: the Antler and Copper World copper-zinc massive sulfide deposits and the Boriana tungsten deposit. The Boriana deposit will not be treated here because there has been no recent production and no significant new data concerning the deposit are available to the authors. The work by Hobbs (1944) is the only available reference on the Boriana. Both the Antler and Copper World mines have had production within the last decade.

Antler Mine

From an initial discovery in 1879 through a number of owners and operators the Antler mine shows a total production of about 78,000 tons with average grade of approximately 3% Cu, 6.5% Zn, 0.75% Pb, 1.1 oz Ag, and 0.01 oz Au (data from Still, 1974). Nearly half of the total production took place during 1970 when the mine was last operational. Mine workings at nine levels (inaccessible at present) extend to a depth of about 700 feet below surface. Standard Metals Corporation acquired the property in 1966 and operated the mine for 10 months in 1970. The operation was terminated due to economic and technical difficulties. In 1974 and 1975 Standard Metals initiated a drilling project and eight drill holes were sunk to explore the deeper ore extensions to the north of the workings.

Although early production from the Antler mine was from high-grade near-surface oxidized ores, all major production has been derived from sulfide ores. The sulfide mineralogy is a simple assemblage of pyrrhotite, sphalerite, chalcopyrite, pyrite (with intergrown magnetite), and galena. Primary mineralization at depth is developed in thin horizons from 0.6 to 12 m, with an overall average of 2.7 m. Along strike the sulfide mineralization extends for at least 730 m. The overall plunge of the orebody is about 63° N. and the dip is to the northwest. At least two intercepts of massive sulfide mineralization were encountered in the deep exploratory holes. Because the underground workings are not accessible, data presented here represent surface observations and drill-core information.

The ore horizons consist of a mix of coarsened sulfides enmeshed in a matrix of cordierite, anthophyllite, biotite-phlogopite, actinolite-tremolite, muscovite, chlorite, garnet, sillimanite, carbonate, epidote, and rare cummingtonite-grunerite. In the drill cores, sulfides, notably pyrite, become conspicuous as phlogopite-anthophyllite is encountered. Chalcopyrite and pyrrhotite also appear. The percentage of disseminated sulfides rises sharply (20-30%) over a distance of 3 to 12 m before the massive sulfide ore is encountered. In all holes examined the sulfide horizon terminates abruptly and is marked by a thin (0.5 m) shear zone against an unmineralized but weakly altered (phlogopite and (or) epidote), apparently siliceous footwall.

Sulfide Mineralogy, Zoning, and Deformation. Pyrrhotite is the most abundant of the sulfide minerals. It is typically found as brownish-pink, plastically deformed masses infilling and surrounding fractured pyrite grains and subhedral silicates. Some samples contain sphalerite inclusions, while in others sphalerite is the later mineral.

Sphalerite and chalcopyrite are intimately intergrown. In reflected light chalcopyrite exhibits a consistent brass-yellow color, while sphalerite is a consistent dark gray.

Pyrite is the less common form of iron sulfide at the Antler mine, whereas it is the most common form at the Copper World mine. It occurs as pale-yellow euhedral cubes (2-5 mm) that are internally fractured and filled with ductile sulfides.

Galena is the scarcest of the sulfide minerals and occurs mostly in the upper meter or so of the massive sulfide horizons, averaging about 1 percent. The galena also carries the silver values, with a 1:1 correlation (1% Pb:1 oz Ag). No other indication of systematic zoning could be recognized from the data available. It seems likely that the consistent, relatively high lead values at the present top of the ore intercepts can only be accounted for by a primary zoning of galena prior to deformation.

A galena sample from the Antler mine was analyzed for lead isotopes. The values obtained are given in Table 1 along with similar isotopic data from two well-known Precambrian massive sulfide deposits of Arizona: the Old Dick deposit at Bagdad and the United Verde deposit at Jerome. From these data a calculated single-stage model age for the Antler deposit is 1.85 b.y., using tables from Doe and Stacey (1974).

Collectively the sulfides are relatively coarse grained as a consequence of recrystallization during deformation and thermal events. The Antler ore samples reveal a contorted and foliated fabric, with plastic flowage of ductile sulfides about silicate knots and brittle pyrite grains. Clark and Kelly (1973) showed that at 300°C and 2 kb pressure pyrrhotite, sphalerite, chalcopyrite, and galena will plastically deform. Metamorphic conditions at the Antler mine clearly exceeded these values. The contorted flowage features would result from thinning of sulfide horizons along the limbs by dislocation of units on either side of the plastic sulfide mass.

Associated Silicate Assemblages. Complex massive fibrous silicate assemblages are closely associated with the Antler orebody, both at the surface and in the subsurface. On the surface due west of the Antler mine shaft is a thickened southwest-plunging synformal fold nose composed of cordierite, anthophyllite, almandine garnet, magnetite, and biotite with a distinctive bladed to rosettelike texture. This trough of fibrous silicates can be traced laterally into thin units of amphibolite and quartz-biotite schist. Nearby, podiform masses of sheared actinolite-tremolite can be found. Similar silicate assemblages, but with even greater mineralogic variety, can be seen in drill-core materials in and near the ore horizons and in waste rock found on the mine dump. Details on the zoning, chemical and textural characteristics of these silicate assemblages can be found in More (1980).

The silicate assemblages mentioned above are believed to represent the metamorphosed remnants of a chloritic alteration mass that was concurrent with the generation of the metals constituting the massive sulfide horizons. The assemblages do not represent an epigenetic hydrothermal replacement of metamorphic rocks but rather a metamorphosed syngenetic product associated with submarine volcanism. To have derived the magnesium and iron required by the silicate assemblage from simple isochemical metamorphism of a volcanic pile would require an initial ultramafic wall rock, a composition not seen in the Hualapai Mountains. Several of the Canadian Archean deposits, as at Rouyn-Noranda, Quebec (de Rosen-Spence, 1969) or the Gull Bridge deposits, Newfoundland (Bachinski, 1976), demonstrate the same thermal metamorphism of discordant chlorite bodies to a silicate assemblage of cordierite-anthophyllite-biotite.

Iron Formation. Iron formation is exposed near the Antler mine and in several localities in the Bulge. At the Antler mine a thin (0.5 m), podiform, pyrite-bearing quartz-magnetite unit, 25 m long, is found conformably within quartz-biotite schist. Massive fibrous silicate outcrops occur within a few meters.

At the Bulge, several thin bodies of iron formation, with associated fibrous silicate masses, occur within foliated quartz–biotite–feldspar rocks near the contact with amphibolite. The iron formations consist of thin discontinuous pods of resistant ferruginous quartzite attaining a maximum thickness of 1.7

Table 1. Isotopic data for galena from three massive sulfide deposits of Arizona

Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Antler mine, Hualapai Mts., Arizona	15.876	15.347	35.463
Old Dick, Bagdad, Arizona[1]	15.805	15.318	35.422
United Verde, Jerome, Arizona[1]	15.725	15.270	35.344

[1]From Stacey and others, 1979

m. Strike lengths rarely exceed 25 m. In thin section the ironstone is seen to consist of granoblastic equigranular quartz, magnetite, and hematite, with hornblende becoming abundant near contacts with amphibolite. The associated fibrous silicate masses typically contain cordierite–anthophyllite–magnetite.

The iron formations are interpreted to be exhalative products closely associated with ore-forming processes (Hutchinson, 1973). The close association with fibrous silicates, the occurrence near the inferred break from felsic volcanism to basaltic volcanism, and the proximity to massive sulfide mineralization (at the Antler) indicate a commonality with other volcanogenic environments in both Canada and central Arizona.

Although there are no know massive sulfides at the Bulge, the iron formations and fibrous silicate masses there show a striking similarity to those present at the Antler mine and suggest a close genetic kinship. The Bulge may be an attractive target area for massive sulfides.

Copper World Mine

The history of the Copper World mine is less well known. Available records begin in the 1940s and show an estimated production of about 16,000 tons of ore, averaging 3.55% Cu, 10.29% Zn, 0.66 oz Ag, and 0.0017 oz Au in the period 1944-1959 (Forrester, 1963). Standard Metals briefly leased the property in 1970 and shipped at least 1,480 tons of ore to the Antler mill.

The mineralization and associated fibrous silicate development at the Copper World mine is approximately identical to that of the Antler mine. In the limited drill core available for inspection, the mineralogy appears to consist of the same sulfide suite except that pyrite far exceeds pyrrhotite in abundance. The silicate assemblage consists of anthophyllite, tremolite, biotite-phlogopite, sillimanite, quartz, chlorite, magnetite, and carbonate. Some dump samples of ore showed carbonate contents up to 12 percent. Wall rocks to the Copper World deposit appear to be meta-rhyolite tuffs. Unlike the Antler mine, amphibolites are not in evidence at the surface and are not mentioned in mine reports. The continuity of sulfide mineralization, the orebody geometry, and the zonation of silicate and sulfide phases are largely unknown because of inadequate subsurface data and poor surface exposures.

Discussion and Conclusions

The western Hualapai plutonic complex is obviously multiphase, but a definitive determination of its intrusive history and its complexity awaits further work along the entire length of the plutonic complex. Spatial relations between the presently recognized phases suggest that the rocks are cogenetic rather than a fortuitous emplacement of magmas widely separated in time.

Kessler (1976) radiometrically dated five plutonic bodies from the northern Hualapai Mountains by ^{87}Rb-^{87}Sr method. Four of these plutons fall in the range 1312-1397 m.y. (errors limits omitted by the authors); the fifth, a granodiorite gneiss, was reported at 1800 m.y. ± 470 m.y. Inasmuch as some of the plutons dated by Kessler may be considered northward extensions of the plutonic complex described here, it is tempting to suggest possible synchroneity of emplacement. Although the timing of plutonic emplacement may indeed prove to be equivalent to events in the northern Hualapais, at this time we resist such correlations and will await the results of future isotopic studies.

The Antler two-mica granite is an intriguing rock unit. Although our data are obviously incomplete, we tentatively suggest that this granitic body may represent a product of partial melting of sedimentary material, that is, an S-type granite (Chappell and White, 1974). Among criteria for S-type granites identified by Chappell and White, we find the following in the Antler granite: a low Na content, high SiO_2, abundant muscovite, absence of hornblende, strong secondary foliation, and abundant micaceous xenoliths. Isotopic data to support or refute this hypothesis are not presently available but, we hope, will be soon forthcoming.

The hornblende-dominant amphibolite units are believed to represent metamorphosed basaltic to andesitic flows and thin tabular intrusions. Present textural variations are probably a reflection of original differences responding variously to dynamothermal and thermal metamorphism. The quartz–hornblende–plagioclase variety of amphibolite, on the other hand, is thought to represent andesitic to dacitic flows or tuffs. The common gradational cyclicity of the two types of amphibolite in a sequence represents a bulk compositional variation that cannot be accounted for by metamorphic segregation processes and therefore must reflect former layering.

The quartzofeldspathic rocks are believed to represent rhyodacitic to rhyolitic tuffs or tuffaceous sediments. Those rocks with a very high quartz content, sometimes approaching 90 percent of the rock, suggest that either a silicified tuff or a sediment derived from rhyolitic tuffs was the protolith. Others containing abundant microcline are probably original rhyolite or rhyodacite pyroclastics or thin flows.

The massive sulfides are viewed as syngenetic, stratiform volcanogenic bodies related to an episode (or episodes) of submarine volcanics, probably in a continent-arc margin environment. Lead isotopic data indicate a Precambrian age generally similar to Bagdad and Jerome, where coexisting rocks have been independently dated by other isotopic methods. Because of structural complications it is not possible to determine whether the Antler system represents one or more cycles of basalt-dacite-rhyolite volcanism. Regardless, the common tendency in Precambrian massive sulfide environments is for the mineralization (and associated alteration) to occur during the waning stages of felsic volcanism (Sangster, 1972; Spence and de Rosen-Spence, 1975). At the Bulge, although massive sulfides are absent, the chert and chlorite protolithic masses (that is, present iron formation and massive fibrous silicates), which at the Antler mine occur with or near the sulfides, are situated at the unique time line defined by the change from rhyolitic to basaltic volcanism. Conceptually, it follows that the basaltic unit is the younger of the sections. If so, we establish a younging direction to the northwest for the entire rock sequence. On the other hand, the stratigraphic sequence of basaltic-to-rhyolitic volcanism followed by sedimentation is common in many central Arizona and Canadian massive sulfide terrains. Equivocally, if our protolith interpretations are correct, the younging direction is to the southeast. Resolution of this conflict awaits further detailed field investigations.

Acknowledgments

We would like to thank the Cavalliere family and George Nasello for logistical assistance during the field work. Paul Gilmour and Arthur Still both provided vital background information on the Antler mine and provided early stimulus to thought on the origin of the deposit. Standard Metals Corporation, Denver, permitted access to the Antler mine property and drill cores. National Science Foundation Grant # EAR 77-09040 supported the work by H. Stensrud; a Duval Corporation Fellowship and Continental Oil Company, Tucson, supplied field and laboratory support for S. More. Lead isotopic analysis was supplied by Maryse Delevaux and Bruce Doe of the U.S. Geological Survey, Denver. Discussions with Phillip Anderson and John Guilbert have materially aided the interpretive phase of the study.

References

Allan, J. W., and Swan, M. M., 1978, Phanerozoic reactivation of Precambrian structure—a significant control on the emplacement of Laramide-age magmas and their related porphyry copper systems in the southwestern United States [abst.]: 5th Symposium IAGOD, Alta, Utah.

Anderson, Phillip, Personal communication: Tucson, Arizona.

Bachinski, D. J., 1976, Metamorphism of cupriferous iron sulfide deposits, Notre Dame Bay, Newfoundland: Econ. Geology, v. 71, p. 443-452.

Chappell, B. W., and White, A. J. R., 1974, Two contrasting granite types: Pacific Geology, v. 8, p. 173-174.

Clark, B. R. , and Kelly, W. C., 1973, Sulfide deformation studies: I. Experimental deformation of pyrrhotite and sphalerite to 2,000 bars and 500°C: Econ. Geology, v. 68, p. 332-352.

de Rosen-Spence, A., 1969, Genesé des roches á cordiérite--anthophyllite des gisements cupro-zinciferes de la région de Rouyn-Noranda, Quebec, Canada: Canadian Jour. Earth Sci., v. 6, p. 1339-1345.

Doe, B. R., and Stacey, J. S., 1974, The application of lead isotopes to the problems of ore genesis and ore prospect evaluation: A review: Econ. Geology, v. 69, p. 657-776.

Ford, T. D., and Breed, W. J., 1976, The younger Precambrian rocks of Grand Canyon; Chapt. 2 *in* Geology of Grand Canyon: Flagstaff, Museum of Northern Arizona, p. 21-33.

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

Hobbs, S. W., 1944, Tungsten deposits in the Boriana district and the Aquarius Range, Mohave County, Arizona: U.S. Geol. Survey Bull. 940-I, p. 247-264.

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

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

More, S., 1980, Geology and mineralization of the Antler mine and vicinity, Mohave

County, Arizona: unpublished M.S. thesis, University of Arizona, Tucson.

Putnam, G. W., and Burnham, C. W., 1963, Trace elements in igneous rocks, northwestern and central Arizona: Geochim. Cosmoch. Acta, v. 27, p. 53-106.

Rasor, C. A., 1946, Loellingite from Arizona: Amer. Min., v. 23, p. 406-408.

Romslo, T. M., 1948, Antler copper-zinc deposit, Mohave County, Arizona: U.S. Bur. Mines Rept. Inv. 4214, Fig. 2.

Sangster, D. F., 1972, Precambrian volcanogenic massive sulfide deposits in Canada: A review: Geol. Survey Canada Paper 72-22, 44 p.

Scott, S. D., 1976, Application of the sphalerite geobarometer to regionally metamorphosed terrains: Am. Mineral., v. 61, p. 661-670.

Spence, C. D., and de Rosen-Spence, A., 1975, The place of sulfide mineralization in the volcanic sequence at Noranda, Quebec: Econ. Geology, v. 70, p. 90-101.

Stacey, J. S., Doe, B. R., Silver, L. T., and Zartman, R. E., 1979, Plumbotectonics IIA, Precambrian massive sulfide deposits: U.S. Geol. Survey Open-File Rept. 76-476, 29 p.

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

Vuich, J. S., 1974, A geologic reconnaissance and mineral evaluation, Wheeler Wash area, Hualapai Mountains, Mohave County, Arizona: unpublished M.S. thesis, University of Arizona, Tucson.

Wilson, E. D., and Moore, R. T., 1959, Geologic map of Mohave County, Arizona: Arizona Bur. Mines, Tucson.

Winkler, H. G. F., 1976, Petrogenesis of metamorphic rocks: New York, Springer-Verlag, 334 p.