ARIZONA GEOLOGICAL SOCIETY DIGEST

VOLUME XI

Proceedings of the PORPHYRY COPPER SYMPOSIUM

TUCSON, ARIZONA / MARCH 18-20, 1976

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A SYMPOSIUM SPONSORED BY THE ARIZONA GEOLOGICAL SOCIETY
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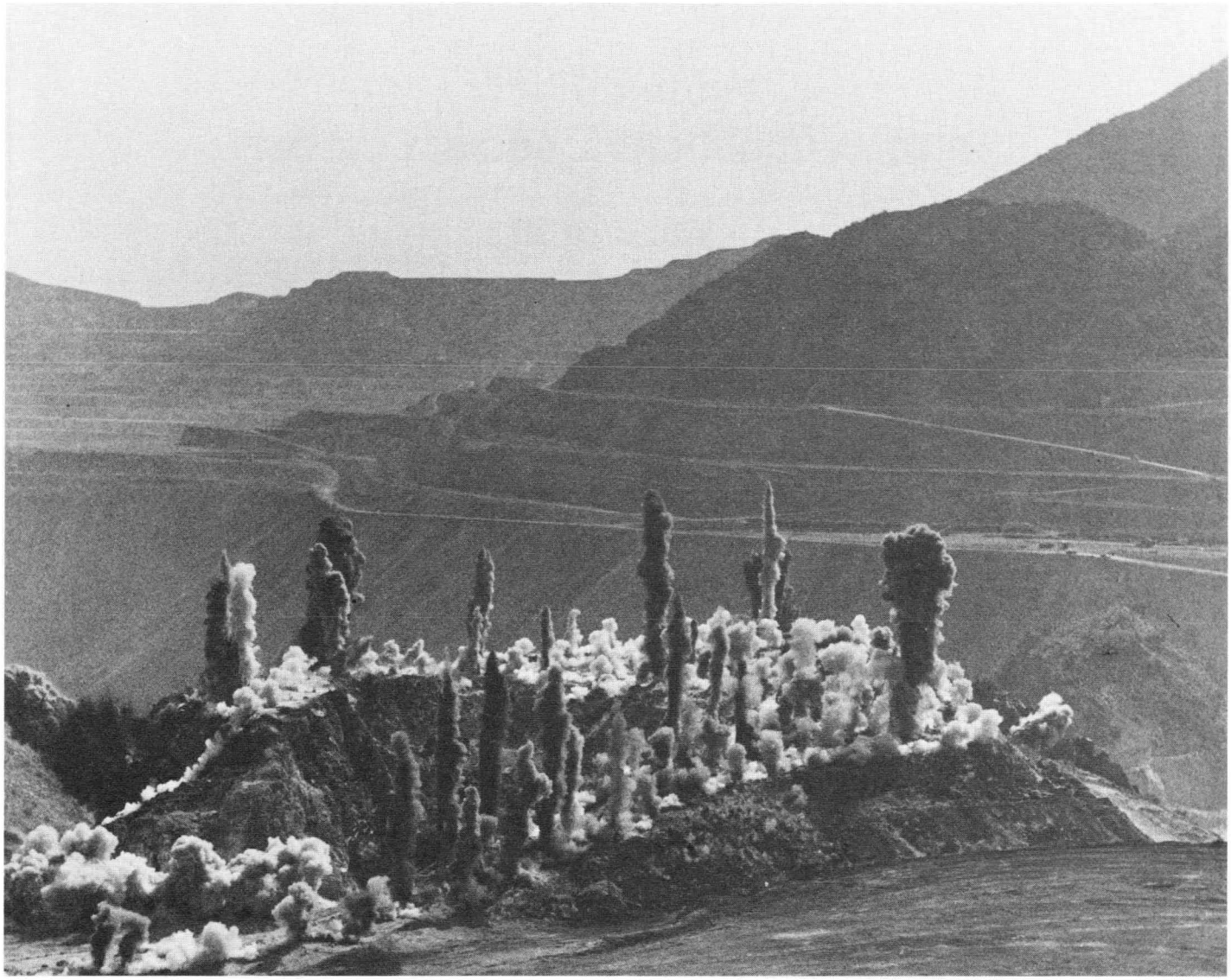
TUCSON, ARIZONA / OCTOBER, 1978



Blasting at Morenci, Arizona—Ray Manley Photography, courtesy of Phelps Dodge

POSTSCRIPT

to

Arizona Geological Society—University of Arizona

PORPHYRY COPPER SYMPOSIUM

March 18-20, 1976
Tucson, Arizona

The Arizona Geological Society was pleased and honored to join The University of Arizona in being the host for this Porphyry Copper Symposium. The continued interchange of words, thoughts, and deeds of the mineral resource industry is indeed rewarding.

Over the past several years, this free exchange of ideas on porphyry copper deposits and exploration has come about with the realization by mining explorationists that more can be gained than lost by presenting scientific descriptions and discussions on mineral deposits and properties. With the impending explosive demand for new mineral deposits, the development of new concepts and ideas and a better understanding of the genesis and occurrence of our mineral deposits are important for our country. The competitive edge a company may hold in the search for new deposits is rarely blunted by release of scientific data on mineral deposits. Rather, the competitive edge is enhanced by the practical synthesis of new ideas and new concepts.

It is therefore particularly gratifying to the organizers of this Symposium to be able to present data on 17 porphyry copper deposits as well as on 13 topical subjects related to porphyry copper exploration and geology. The inclusion of reports of nearly half the known porphyry copper deposits in the southwestern United States about which little or no information has been released is an indication of the mineral worth of this sector.

This outstanding free exchange of ideas and data—incorporated in a symposium—was provided by a combination of 14 mining companies, 3 consultants, 5 universities, and the U.S. Geological Survey. This represents an outstanding realization of the purpose of our Symposium.

Undoubtedly many more porphyry deposits will be found by explorationists both here and in adjacent areas, and may the spark that generated and expanded the concept into a viable commodity have been fed by the association of the past days and nights!

We hope that this free exchange can be continued in the future with more symposiums, scientific meetings, and publications. We as individuals working in porphyry copper geology can only increase our knowledge and understanding of our field; as a result, both we and our companies are the ultimate beneficiaries of this Symposium.

James D. Sell and Charles P. Miller
Co-General Chairmen

March 19, 1976

PREFACE

No serious reader of this Digest can be unaware of the state of the copper mining industry in 1978 nor need be cautioned that these articles reflect economic conditions of 1976 and technical developments to that time. Although publication of these articles had been delayed in part by the depressing events following the Symposium, the Society believes that papers of a descriptive nature remain sufficiently current to warrant publication at this time. Some papers given at the Symposium were not available, and abstracts were reprinted from the Symposium program in the interest of completeness. Expanded abstracts were furnished by some authors in lieu of full-length manuscripts. Current affiliations of authors are provided.

The editors acknowledge Dr. Evans B. Mayo, Professor Emeritus of Geosciences, The University of Arizona, for critical review of many of the papers and Dr. John S. Sumner of the Department of Geosciences, The University of Arizona, for technical assistance. We are especially grateful to the various authors for their patience and courtesy during this period of delayed publication.—The Editors.

September 1978

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The Digest is issued periodically by the Society as an informal bulletin intended to present technical papers and progress reports of research bearing on geological problems of Arizona in particular and the Southwest generally. The editor welcomes such papers as well as notes and news of geological and related activities within this broad framework.

Manuscripts submitted for publication should meet the following requirements:

1. Manuscripts must be typewritten and double spaced throughout (including abstracts, quotations, and list of references cited).

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3. Abstracts, not exceeding 300 words, are required for all articles.

4. Drafted illustrations should be carefully prepared in waterproof black ink on drafting stock or Mylar. Lettering should be done with lettering guides or machines. Size of illustration and lettering and especially patterns should permit reduction to Digest format. Consultation with the editor is invited to determine current format. Illustration titles should be typed on a separate sheet of paper and not lettered on the illustrations.

5. Photographs should be sharp, glossy, black-and-white prints and kept to a minimum.

6. The original and one copy of the manuscript, including illustrations, should be submitted. Manuscripts and inquiries may be addressed to:

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SILICATE MINERAL ASSEMBLAGES AND THEIR RELATIONSHIP TO SULFIDE MINERALIZATION, PINOS ALTOS MINERAL DEPOSIT, NEW MEXICO

by

J. F. McKnight[1] and M. L. Fellows[2]

Abstract

The Exxon Company, U.S.A. Pinos Altos skarn-associated mineral deposit is favorably situated in southwestern New Mexico near the Central and Tyrone mining districts and lies in a broad structural uplift that contains a complex sequence of Laramide intrusions. The mineral deposits of the Pinos Altos district are within and around the Pinos Altos quartz monzonite stock, which is emplaced into a thick section of Paleozoic strata and Cretaceous sedimentary and volcanic rocks.

Historic production in the district came from numerous northeast-trending metalized fissure veins and from limestone replacement bodies west of the stock. Metal zoning is exhibited in these veins and replacements, with copper predominant over zinc, lead, and silver in the northern part of the district. Moreover, the intensity of calc-silicate alteration in the replacements increases northward. Thus mineral and alteration zoning suggested that copper-rich skarn mineralization might be found in reactive Paleozoic strata at depth adjacent to the north end of the Pinos Altos stock.

Drilling adjacent to the north end of the Pinos Altos stock has intercepted copper-zinc-silver sulfide mineralization in calc-silicated Paleozoic strata. Chalcopyrite, sphalerite, pyrite, magnetite, specular hematite, and a variety of silver sulfides and sulfosalts are interstitial to the calc-silicates. Sulfide and iron oxide minerals are zoned with respect to the stock—wall-rock contact. Magnetite-chalcopyrite occurs close to the stock and gives way outwards to chalcopyrite-sphalerite and then to pyrite-sphalerite.

Most of the mineralization occurs in three principal zones in the impure limestones of the Pennsylvanian Magdalena Group. Three alteration stages are discernible. The first is an essentially isochemical thermal metamorphic stage. The second is a metasomatic episode in which iron, silica, sulfur, and base metals were added to the wall rocks forming a massive garnet-quartz-calcite skarn with minor amounts of iron oxides and base-metal sulfides. Major sulfide deposition began late in this metasomatic stage and continued into the subsequent retrograde alteration stage—the third alteration event. This retrograde or silicate-destructive phase probably took place in the presence of a hydrous fluid as temperature decreased.

Introduction

The Exxon Company, U.S.A., mineral prospect at Pinos Altos, New Mexico, was a direct outgrowth of a study of old mining districts, which was undertaken in 1971 to establish exploration priorities among the various New Mexico mining areas. The study consisted of a survey of available literature and Exxon reports to determine mineral and structural trends and district habits that might help locate as yet undiscovered ore deposits. Pinos Altos ranked high in this survey.

[1] Exxon Minerals Co., U.S.A., Silver City, New Mexico 88061

[2] Exxon Minerals Co., U.S.A., Tucson, Arizona 85705

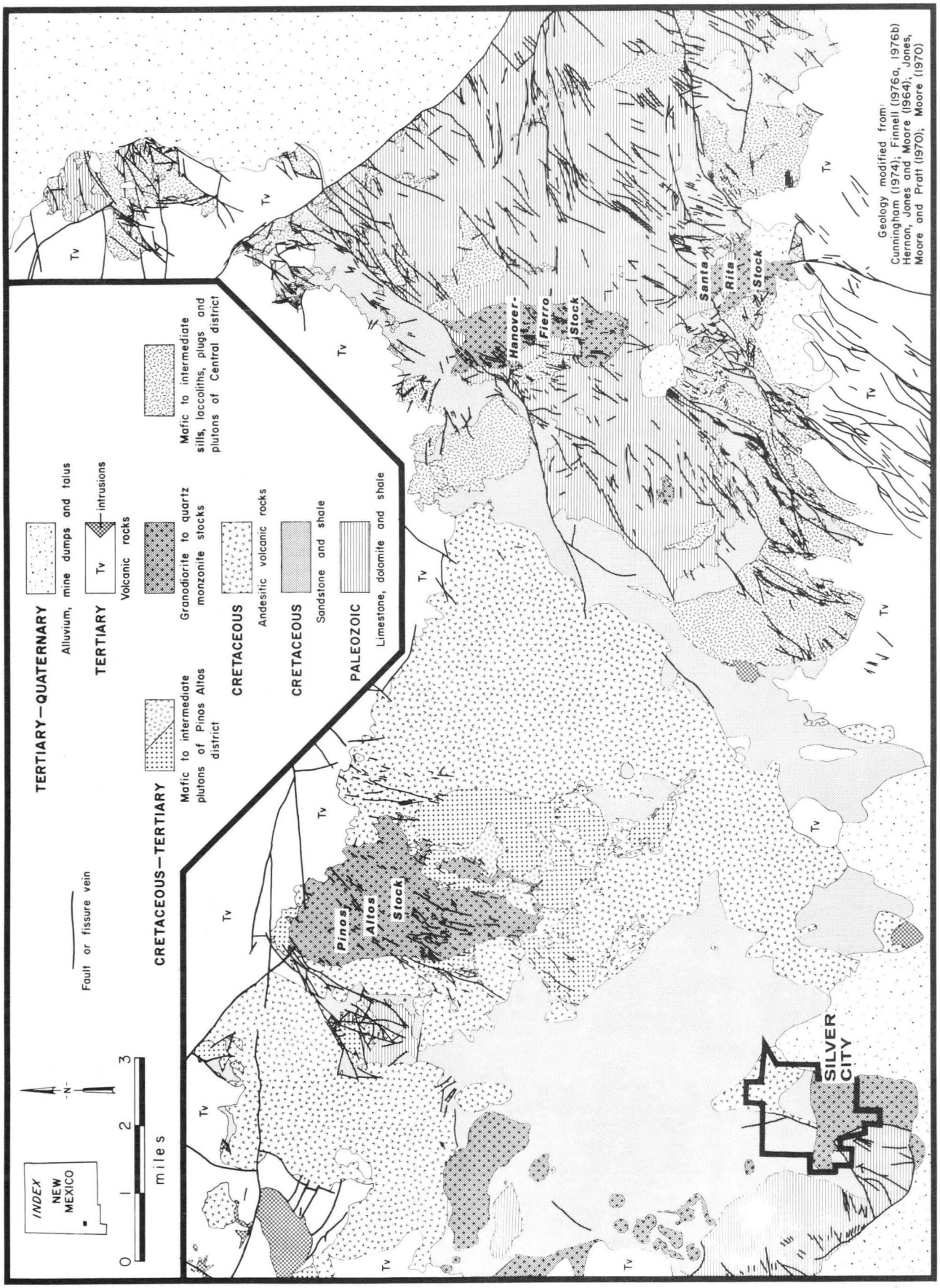

Fig. 1. Generalized geologic map of the Silver City mining region

Geologic Setting and Exploration History

The Pinos Altos prospect is located about eight miles north of Silver City, New Mexico (Fig. 1). The district is favorably situated in a metallized region, including the Central mining district 10 miles to the east and the Tyrone district 18 miles to the southwest. The area covered in Figure 1 is termed the Silver City mining region following the usage of Jones, Case, and Pratt (1964). The region is a broad structural uplift that contains a complex sequence of differentiated Laramide igneous rocks. The diversity of rock types is evident in mapping by Hernon, Jones, and Moore (1964) and by Jones, Moore, and Pratt (1970), who show seventeen different Laramide intrusive rock types in the area. Several medium-grained, multiple-phase granodiorite to quartz monzonite porphyry stocks occur in this region, most of which have associated base and precious metal mineralization. The stocks at Santa Rita, Hanover-Fierro, and Pinos Altos are perhaps the more well known of these metallized intrusions.

Late Cretaceous andesitic volcanic rocks similar to those commonly associated with southwestern porphyry copper deposits cover a large part of the area, particularly around the Pinos Altos district. The volcanic rocks overlie unconformably either Upper Cretaceous clastic rocks of the Beartooth Quartzite or Colorado Formation or Paleozoic carbonate strata. These sedimentary and volcanic rocks (Table 1) are the hosts for many of the Laramide intrusions and much of the mineralization in the region.

The Pinos Altos intrusive complex consists of a variety of mafic to intermediate intrusions peripheral to the Pinos Altos stock, a later multiple-phase mass of quartz monzonite (Fig. 2). Rocks of the complex are fresh to moderately chloritized and contain at most only a few tenths of a percent pyrite. McDowell (1971) reported potassium-argon dates of 72.6 + 2.2 m.y. and 69.1 $\pm$ 2.1 m.y. on hornblende collected near the center of the Pinos Altos stock. These values are in close agreement with a less precise potassium-argon value of 68 $\pm$ 8 m.y. that Exxon obtained through Dr. J. A. S. Adams of Rice University.

Northwesterly and northeasterly trending faults display a braided structural fabric characteristic of metallized porphyry districts. This fault pattern coupled with northeasterly trending dikes and fissure veins indicates pronounced northwest-southeast extension. Numerous northeasterly trending metallized fissure veins are exposed in the Pinos Altos stock and in the Cretaceous wall rocks (Fig. 2), and

Table 1. Generalized premineral stratigraphic section in the Silver City mining region

AGE	FORMATION		DOMINANT LITHOLOGY	APPROXIMATE THICKNESS (FT.)	CHARACTER AS HOST FOR MINERALIZATION
Cretaceous	Andesitic volcanic rocks		Flows, breccia and tuff	300-1000	Poor
Cretaceous	Colorado Formation		Sandstones and shale	300-2200	Poor
	Beartooth Quartzite		Orthoquartzite sandstone, some conglomerate	60-140	Poor; calcareous beds permissive
Permian	Abo Formation		Red shale, partly calcareous	0-265	Fair to excellent for deposits in thermal metamorphic skarn
Pennsylvanian	Magdalena Group	Syrena Formation	Argillaceous silty limestone, calcareous siltstone, shale	0-390	Good to excellent for deposits in thermal metamorphic skarn
		Oswaldo Formation	Limestone, calcareous siltstone, shale	450-490	Excellent for metasomatic replacements
Mississippian	Lake Valley Limestone		Limestone, partly cherty and argillaceous	300-480	Excellent for metasomatic replacements
Devonian	Percha Shale		Shale, upper member calcareous	350-430	Poor
Silurian	Fusselman Dolomite		Dolomite	200-300	Poor; permissive for small metasomatic replacements
Ordovician	Montoya Dolomite		Dolomite and limestone with chert	200-350	Poor; permissive for small metasomatic replacements
	El Paso Limestone		Silty dolomite and limestone	520	Fair for metasomatic replacements; good for deposits in thermal metamorphic skarn
Cambrian-Ordovician	Bliss Formation		Sandstone and shale	190	Poor
Precambrian			Granite		Poor

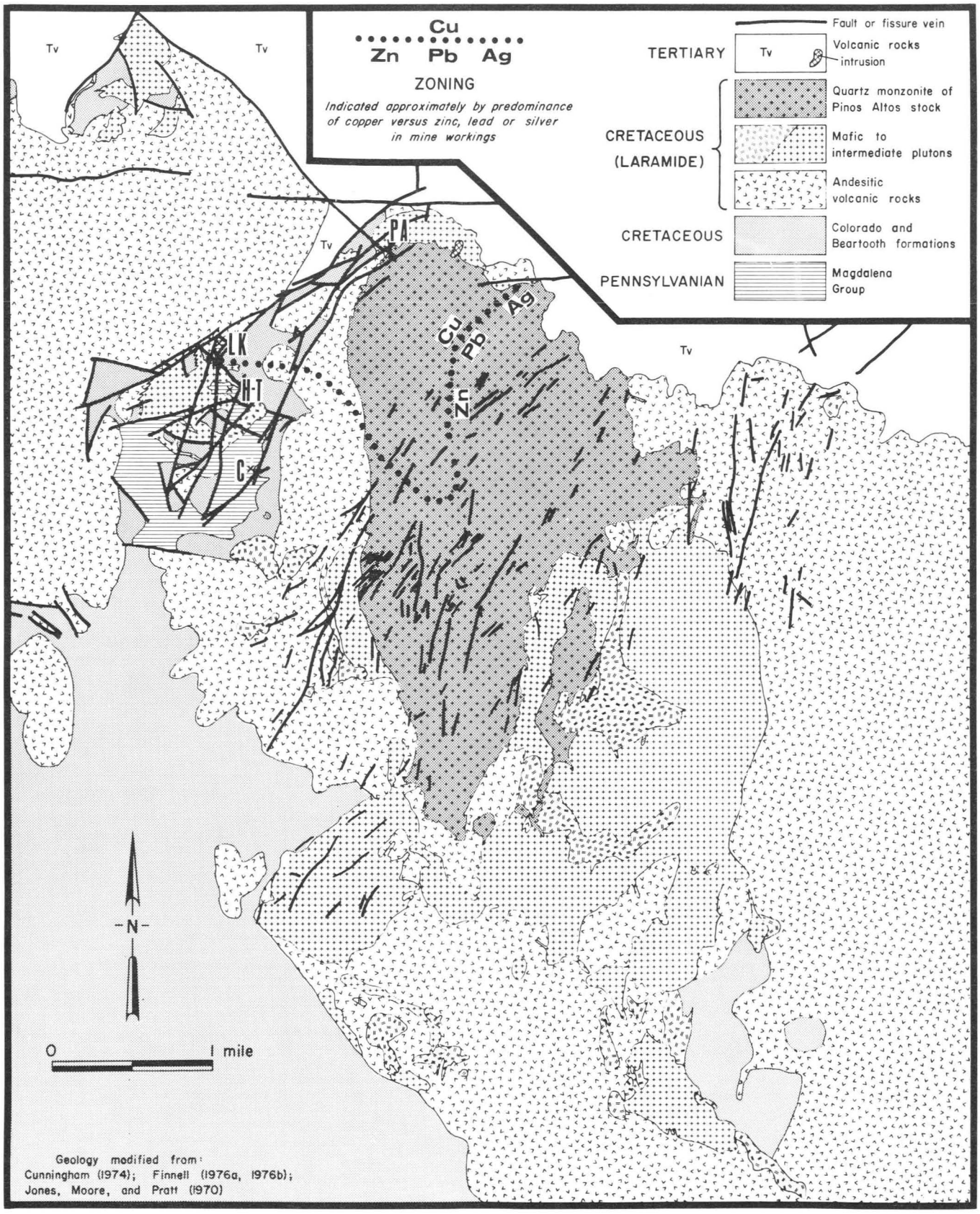

Fig. 2. Geologic map of Pinos Altos district. Abbreviations west of Pinos Altos stock refer to localities discussed in text: C, Cleveland mine; H-T, Houston-Thomas mine; LK, Lady Katherine prospect; PA, Pinos Altos prospect.

many mine workings exploited these veins. Visible mineralization on the dumps of these workings include both hypogene and supergene sulfides and oxides of copper, zinc, silver, and lead. Many of the veins in the Pinos Altos district have produced significant amounts of gold. Quartz-pyrite is the common gangue in the veins which characteristically have sericitic selvages. Zoning is indicated by abundant copper mineralization at the north end of the stock and by a strong partial halo of zinc-lead-silver across the middle and south end of the intrusive complex (Fig. 2). Sparse molybdenite occurs in some northeasterly trending quartz veins in the north-central part of the stock.

Most of the historic production in the district came from replacement and skarn deposits in Pennsylvanian Magdalena Group limestone exposed west of the Pinos Altos stock. The greatest production came from the Cleveland mine (C on Fig. 2), which produced zinc and lead from replacement deposits; judging from rock on the dump, the host is weakly chloritized marble from the Magdalena Group. Lesser production came from the Houston-Thomas mine (H-T) area to the north, but these workings produced some copper as well as lead and zinc. The Magdalena limestone in the Houston-Thomas workings contains actinolite as well as abundant chlorite. The northernmost block of limestone west of the stock occurs at the Lady Katherine prospect (LK), where chalcopyrite and minor sphalerite occur with pyrite along fissure veins in the Magdalena. Here, the Magdalena is altered to a relatively high temperature skarn assemblage of garnet, diopside, actinolite and calcite.

Thus, observations at the old workings indicate metal and alteration zoning about a source to the north where the permissive Paleozoic carbonate strata are covered by Cretaceous clastic rocks and andesitic volcanic rocks. In this area, hematitic goethite occurs along fractures in an upthrown block of the Colorado Formation. The sandstone is nonreactive and therefore not obviously altered, but vuggy quartz thinly coats sparse fractures. In addition, small adits, shafts, and prospect pits occur along fissure veins, which contain feeble to modest copper mineralization.

Cretaceous andesites in this area are weakly propylitized but are not obviously more altered than andesites elsewhere along the periphery of the stock. Thermal metamorphism has converted the andesite to a hornfels in the vicinity of the Pinos Altos stock.

General Geology of the Mineral Deposit

The geology and zoning suggested that skarn-associated sulfide mineralization might exist in Paleozoic carbonate strata adjacent to the north end of the Pinos Altos quartz monzonite stock; the permissive strata are covered by Cretaceous clastic sediments, Cretaceous andesites, and postmineral mid-Tertiary sediments and volcanic rocks (Fig. 2). Exxon's drilling program to test this target began in 1973 and delimited copper-zinc-silver sulfide mineralization in calc-silicated Paleozoic carbonate strata. Most mineralization occurs in the Pennsylvanian Magdalena Group, but some mineralization also occurs in the Mississippian Lake Valley Limestone and in the lower Paleozoic formations. (Table 1). The Paleozoic strata are essentially flat-lying and separated from the overlying Cretaceous clastic sedimentary rock by a disconformity. In the mineralized area the top of the Paleozoic section ranges from 350 to 1,700 feet beneath the surface.

Mineralization on the west side of the stock occurs in specific zones in the Syrena and Oswaldo Formations which comprise the Magdalena Group. The most extensive, the "upper" mineralized zone, is directly beneath the Cretaceous Beartooth Quartzite (the Permian Abo Formation being locally absent beneath the unconformity at the base of the Beartooth). A second mineralized zone, the "lower" zone, occurs at the contact of the carbonate wall rocks with the Pinos Altos stock. Several mineralized intervals between the upper and lower zones probably follow favorable lithologies in the Magdalena.

Stratigraphy and Skarn Facies

The Syrena Formation is predominantly argillaceous-silty limestone and calcareous siltstone, but it also contains abundant interbedded siltstone and shale; pure carbonate units are uncommon. The lithologic character of the Oswaldo Formation resembles that of the Syrena, but the Oswaldo contains less argillaceous material, more carbonate and more clean limestone units. Thus, the overall calcium carbonate content of the Magdalena Group increases downward. Both the Syrena and Oswaldo characteristically vary in lithology over short lateral and vertical distances.

The Paleozoic strata are subdivided into five basic types of host rock, each of which alters to a distinctive suite of metamorphic and metasomatic minerals (Fig. 3). Most of the mineralization found to date occurs in the argillaceous-silty limestone and calcareous siltstones.

Alteration and mineralization was a continuous process which can be described as occurring in three more or less well-defined stages.

HOST	METAMORPHIC	METASOMATIC	RETROGRADE
LIMESTONE Pure Cherty	**MARBLE** recrystallized Calcite Wollastonite	Andradite Quartz Calcite	Chlorite Calcite Quartz
ARGILLACEOUS SILTY LIMESTONE and CALCAREOUS SILTSTONE	**SKARN OR MARBLE** Calcite → Wollastonite Idocrase Grossularite Diopside Talc Tremolite Clinozoisite Pyrite / Pyrrhotite	Magnetite Pyrite Specularite Diopside Wollastonite Hedenbergite Sericite K feldspar Epidote	Clay Actinolite Talc Sericite Epidote Siderite – Ankerite Zeolites Gypsum Pyrite
SILTSTONE	**HORNFELS** Chlorite → Diopside	Siderite – Ankerite Scapolite Chalcopyrite	Sphalerite Chalcopyrite Galena
MUDSTONE and SHALE	**HORNFELS** Chlorite → Biotite → K feldspar Albite Garnet	Sphalerite Pyrrhotite Molybdenite	Hematite Magnetite
DOLOMITE Pure Siliceous	**MARBLE** recrystallized Dolomite Talc → Tremolite → Diopside	Talc Diopside	Talc

Fig. 3. Generalized skarn facies associated with five basic Paleozoic rock types at Pinos Altos. Common minerals are listed in larger type than uncommon minerals. Arrows indicate a temperature-related reaction series between minerals.

The first stage was essentially isochemical or nonadditive thermal metamorphism. A metasomatic stage followed in which abundant quantities of iron, silica, sulfur, and base metals were added to the wall rocks, presumably from the intrusion. Metasomatic replacement, although clearly favoring carbonate sections, was superimposed on nearly all host types except the shales and dolomites. Thermal metamorphism and silica-iron metasomatism are interpreted to have taken place under conditions of rising temperature and are therefore termed prograding events. The third, or retrograde, stage probably took place as temperature waned in the presence of a fluid rich in water. Alteration of previously formed skarn minerals characterized this stage. Deposition of sulfides and iron oxides began during metasomatism and continued into the retrograde stage.

Thermal Metamorphism—Metamorphic Skarn

Of the three alteration events, the thermal metamorphic episode produced the most varied mineral assemblages (Fig. 3), as a consequence of the compositional variety of original host rock types. In pure limestone and dolomite, for example, thermal metamorphism resulted in the simple recrystallization of the component carbonate. Where silica was available, wollastonite developed in limestone. Metamorphism of argillaceous and silty limestones along with calcareous siltstones produced a variety of minerals including wollastonite, idocrase, grossularite, and diopside. Several other minerals (Fig. 3) are present though not abundant. These metamorphic minerals tend to form selectively in the argillaceous and silty fraction of the rock, where it is in contact with calcite, thus preserving primary sedimentary textures.

Siltstones are converted to two hornfels assemblages: quartz-chlorite formed at relatively low temperatures, and quartz-diopside formed at higher temperatures. Mudstones and shales are metamorphosed to biotite hornfels adjacent to the stock and to chlorite hornfels farther from the stock. The biotite hornfels locally contains sparse amounts of orthoclase and garnet.

Metasomatic Skarn

Metasomatic skarns are superimposed upon and locally obliterate thermal metamorphic skarns. The metasomatic skarns contain relatively few minerals. Andradite, quartz, and calcite comprise the bulk of the rock (Fig. 3) and characterize an assemblage here designated as "garnet skarn." Magnetite, pyrite, specularite, diopside, and base-metal sulfides commonly occur in small amounts. Sparse, minor constituents of the metasomatic skarns include hedenbergite and an iron-bearing wollastonite. Metasomatic garnet skarns generally replace beds en masse but favor pure limestone beds, traveling farther from the intrusion in these more susceptible units (Fig. 4). As a consequence of this selective replacement process, an erratic marble line is developed. Magnetite and hematite are distributed throughout the garnet skarn but generally die out toward the metasomatic front separating the skarn and the unsilicated wall rocks. Sulfides likewise occur sporadically throughout the garnet skarn, and some sphalerite actually occurs in marbles outside of the skarn.

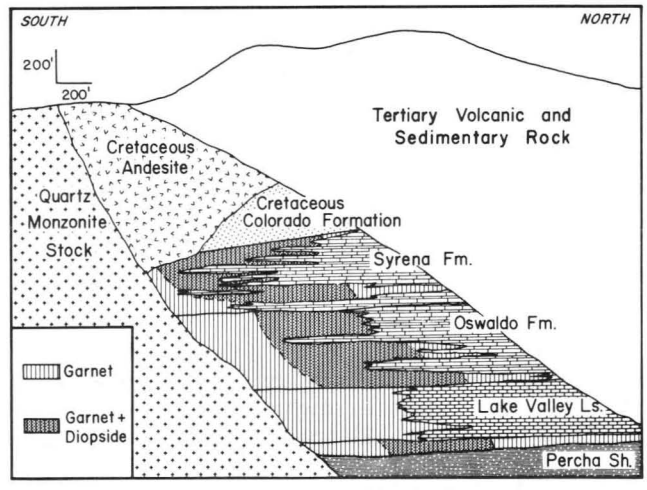

Fig. 4. Schematic section across the north side of the Pinos Altos stock showing the distribution of skarn types.

Diopside in the garnet skarns is relict from prograde thermal metamorphism inasmuch as it occurs only in magnesium-bearing strata of the Magdalena Group and in the Box or upper member of the Percha shale. Diopside is absent in the massive garnet skarns formed from the clean Lake Valley Limestone.

Thus, compositional changes from bed to bed control the degree to which the various strata are affected by thermal metamorphism or metasomatism. The impure carbonates of the Syrena form diopside-bearing metamorphic skarns upon which metasomatic garnet skarns are superimposed. The Oswaldo Formation, with a higher proportion of limestone, forms a massive garnet skarn containing less diopside, and skarns formed in the Lake Valley Limestone are entirely metasomatic garnet skarns (Fig. 4).

Alteration of the lower Paleozoic strata is poorly known. A few holes have penetrated the Ready Pay or lower member of the Percha Shale which is baked to a chlorite-biotite hornfels but is not affected by metasomatism. Talc and diopside, intercepted in Ordovician dolomites near the stock contact, probably developed through additions of silica and water, rather than from isochemical thermal metamorphism.

Retrograde Alteration

Retrograde alteration affected the metasomatic and to a lesser extent, the metamorphic skarns. The minerals produced during this stage are characteristically the hydrous phases—chlorite, clay, actinolite, talc, and sericite (Fig. 3). Calcite, quartz, iron oxides and sulfides also occur in this assemblage. A variety of other minerals is also present, but their distribution is sparse and sporadic.

Mineral assemblages characterized as retrograde either replace earlier formed metamorphic and metasomatic minerals or occur interstitially to metasomatic skarn minerals. Retrograde alteration affects prograde skarns to varying degrees from slight alteration of the edges to complete replacement of the silicate grains.

Sulfide Distribution and Paragenesis

Copper-zinc-silver-iron sulfides and iron oxides are interstitial to the calc-silicates, and the sulfides may or may not be found with associated retrograde alteration minerals. For example, the upper zone contains extensive retrograde alteration products associated with mineralization, whereas in the lower zone, sulfides and iron oxides occur in generally unaltered prograde metasomatic skarn. Mineralization typically occurs with retrograde alteration in pervasive stockwork fractures.

Sulfide and iron oxide minerals in the upper zone are apparently zoned with respect to the stock—wall rock contact. Figure 5 illustrates the typical mineral zoning and paragenesis observed. Magnetite was deposited early; it is abundant near the stock but diminishes abruptly outward. With time and with increasing distance from the stock, chalcopyrite and pyrite become the major iron-bearing phases reaching successive peaks and then declining. Later sphalerite and galena are the predominant sulfide minerals in the distal parts of the mineralized zones. The volume of sulfides increases outward, reaching a maximum in the pyrite-chalcopyrite-sphalerite zone, and then decreasing.

Mineral distribution in the lower mineral zone differs in several respects from that in the upper zone. The lower zone generally contains smaller bodies of higher grade chalcopyrite mineralization. In addition, detectable chalcopyrite is present over a much broader area in the lower zone. Furthermore, magnetite is more abundant in the lower zone, whereas pyrite is less abundant in the lower zone than in the upper zone.

The paragenetic sequence (Fig. 6) is essentially the same in all zones. Prograde calc-silicate formation was followed by iron oxides and a wide variety of copper, zinc, silver, lead, and bismuth sulfides. Although much of the sulfide deposition accompanied the silicate-destructive retrograde event, significant mineralization does occur without obvious retrograde effects on associated silicates.

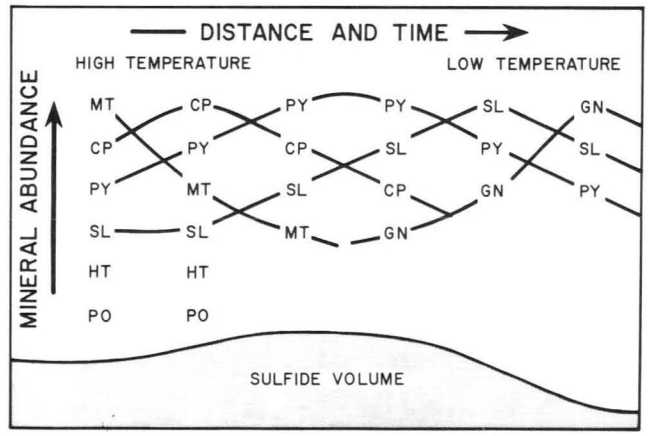

Fig. 5. Schematic sulfide-oxide zoning sequence at Pinos Altos as a function of time and distance from the Pinos Altos stock

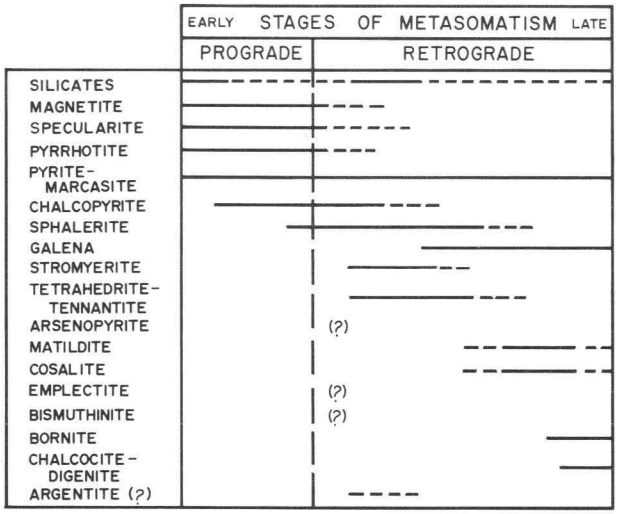

Fig. 6. Generalized paragenetic sequence for ore zones at Pinos Altos. The minerals arsenopyrite, emplectite, and bismuthinite have been definitely identified, but their position in the paragenetic sequence is uncertain. A mineral tentatively identified as argentite occurs early in the paragentic sequence. (Mineral identifications by A. L. Kidwell, Exxon Production Research Co.)

Acknowledgments

This paper is based on the work and thoughts of the numerous people who have worked on the Pinos Altos Project. We gratefully acknowledge our associates, D. A. Dean, J. D. Dolence, and R. G. Rowe, for assistance in mapping; J. F. Ward for stratigraphic information; A. L. Kidwell for mineral identifications; and L. D. Hayes, N. G. Lavery, J. D. Mancuso, and R. R. Weaver for their ideas and effective supervision of the project. We also acknowledge the support of the management of the Minerals Department, Exxon Company, U.S.A., who have permitted the publication of this material.

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GEOLOGIC STRUCTURE OF THE SAFFORD DISTRICT, ARIZONA

by

Peter G. Dunn[1]

Abstract

The Safford mining district is restricted to a 15-mile-long, northwest-trending belt of Eocene igneous rocks along the southwestern flank of the Gila Mountains in Graham County, Arizona. It includes two major and two smaller porphyry copper deposits and is one of the largest districts in the Southwest as measured by the amount of copper metal.

Premineral andesitic extrusive rocks, including bedded and crystal tuffs emplaced in volcanic vents, have been intruded by a quartz diorite stock, a series of latite and quartz latite dikes, and several small quartz monzonite porphyry intrusions. The rocks are comagmatic and yield K-Ar age dates ranging from 58 to 53 m.y. The copper mineralization is directly related to the quartz monzonite bodies.

The principal structural features of the district include faults parallel to the elongation of the premineral outcrop and northeast to east-northeast structures that controlled mineralization at the individual deposits. The northwest-striking faults include the Butte fault, which extends the full length of the district and has as much as 4,000 feet of vertical displacement. Other northwest faults have offset the Sanchez deposit and controlled the distribution of oxide and supergene ore at the Kennecott deposit. These faults were presumably controlled by the same regional structures that caused the rough alignment of the porphyry copper deposits in the district.

The northeast-striking structures include dike swarms and mineralized fractures; faults have been difficult to map because of the lack of marker units in the andesite. These northeast-striking faults have no more than a few hundred feet of vertical displacement measured at the base of the postmineral volcanic rocks. They have been in existence since the period of mineralization, however, and may have had as much as 1,500 to 2,300 feet of vertical displacement since the intrusion of the quartz monzonite porphyry stocks.

Introduction

The Safford, or Lone Star, mining district is in Graham County in southeastern Arizona about 95 miles northeast of Tucson and about 18 miles southwest of Morenci (Fig. 1). Four separate porphyry copper deposits occur within a narrow northwest-trending belt of Eocene igneous rocks along the southwestern flank of the Gila Mountains. The belt of premineral outcrop is about 15 miles long and a little over two miles wide at its widest part. The premineral rocks are covered by postmineral volcanic rocks to the northeast and are bounded by a major normal fault to the southwest (Fig. 2). The porphyry copper deposits include the very large Kennecott and Phelps-Dodge deposits, the Sanchez deposit held by Inspiration Copper and the small San Juan deposit. Production from the district to date has been limited to an intermittent leaching operation at the San Juan, but the Lone Star district, as measured by the amount of copper metal, is one of the largest districts in the southwest.

The district has been an area of active exploration for more than 20 years, but very little information has been published on it. This paper is a compilation of my mapping in the Kennecott area and in the northwest end of the premineral outcrop where Quintana Minerals had been working. The compilation also includes previous mapping by Kennecott and Bear Creek geologists, by other Quintana geologists who had worked in the district, and from a Master's thesis at the University of Arizona on the San Juan deposit (Blake, 1971). I have been given permission by both Kennecott and Quintana to publish this

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Fig. 1. Location map, Safford district

paper, but I am solely responsible for the structural interpretation.

Geology

The premineral rocks in the district include a thick sequence of andesite flows and agglomerates that have been intruded by the Lone Star quartz diorite stock, latite and quartz latite dikes, and several quartz monzonite porphyry stocks which are directly related to the porphyry copper mineralization. Mappable units within the andesite are rare. Drill holes up to 4,000 feet deep in the district have failed to reach the bottom of the sequence. This extreme thickness, together with the lack of obvious flow structures in most of the andesite, and the lack of a sharp contact between the andesite and the quartz diorite in drill core suggest that part of the andesite may have been formed as hypabyssal intrusions.

The quartz diorite forms several small plugs and dikes in addition to the Lone Star stock. It is not directly related to the copper mineralization anywhere in the district, although it does form the host rock of some of the primary mineralization in the Kennecott deposit. Several large xenoliths of Precambrian(?) granite and Cambrian(?) quartzite occur within the stock.

A near-vertical pipe of well-mineralized tuff is exposed near the center of the Kennecott deposit. The exposure is nearly 6,000 feet long in the northwest direction, and the tuff extends at least 4,000 feet to the northeast beneath the postmineral volcanic cover. It is exposed in the underground workings and in a single small outcrop behind the range front. On the surface and underground, the contact between the andesite and the mineralized tuff is nearly vertical. The tuff extends at least 2,000 feet vertically, but the nature of the contact between the tuff and the andesite is not known—no bottom has yet been found (Fig. 3). Part of the tuff is well-bedded with dips 30 to 50 degrees toward a common center, suggesting a collapse origin caused by removal of magma at depth. A much smaller outcrop of mineralized tuff occurs about a mile and a half to the southeast.

The youngest of the premineral rocks in the district are the stocks of quartz monzonite porphyry, each of which is associated with disseminated copper mineralization. Small quartz monzonite porphyry stocks are exposed at the San Juan and Sanchez deposits, and nearly identical rocks have been encountered at depth at both the Kennecott and Phelps-Dodge deposits. The smaller bodies of quartz monzonite porphyry at the Horseshoe mine and between it and the Sanchez deposit also contain minor copper mineralization. The four principal porphyry stocks occur as narrow near-vertical cylinders close to the center of each sulfide system.

The andesite and quartz diorite have both been cut by numerous latite and quartz latite dikes, dikes which could not be shown on the accompanying geologic map (Fig. 2). The dikes are generally 5 to 20 feet wide, and most occur as northeast-trending swarms. The two rock types can be distinguished in the field by the presence or absence of large quartz phenocrysts, and the two types are separated in time by the period of formation of the mineralized tuff. Dike fragments within the tuff consist only of latite, while only quartz latite dikes cut the tuff. An interpretation with possible exploration significance in the Safford district is that the latite dikes are related to the quartz diorite and that the quartz latite dikes are related to the quartz monzonite porphyry stocks.

The comagmatic origin of the premineral igneous rocks is indicated by the smooth curves on the variation diagram (Fig. 4). Whole-rock chemical analyses were made of unaltered andesite, quartz diorite, and dike rocks taken from the outcrop area southwest of the Kennecott deposit. This postulated comagmatic origin is supported by the narrow range (58-53 m.y.) of K-Ar age dates for the igneous rocks and a 53 m.y. date for the sericite at the Kennecott deposit (Robinson and Cook, 1966).

The postmineral volcanic rocks in the Safford district can be divided into three units: older andesitic basalt flows, a series of siliceous units including tuffs and rhyolite plugs, and younger basalt flows with thin interbedded tuffs. Tuff breccia at the base of the younger basalt flows contains fragments of leached capping. The postmineral units dip 10-15° NE., and this appears to be the total tilting of the district.

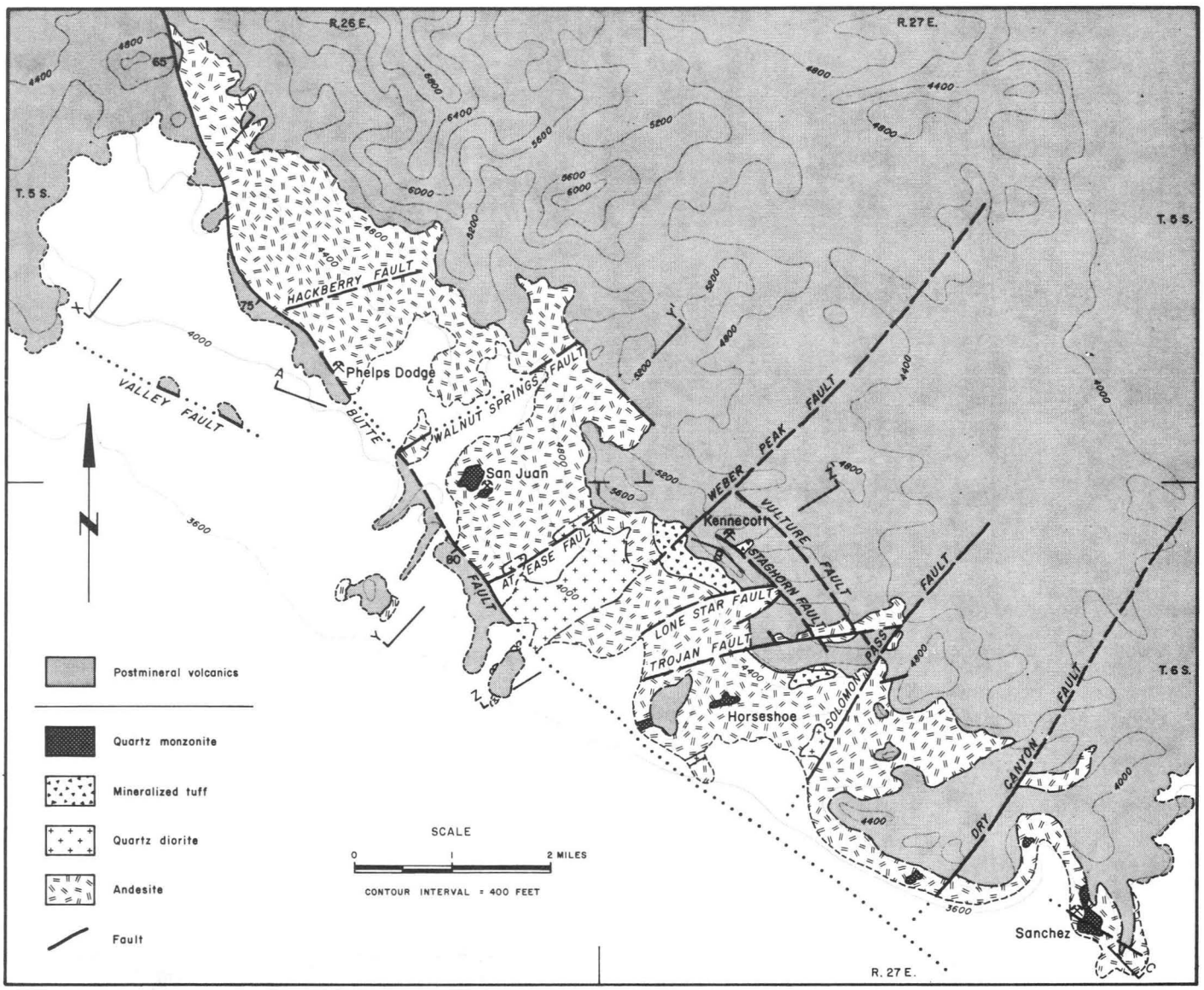

Fig. 2. Geologic map, Safford district

Structure

The Safford mining district shows two principal structural directions—northwest faults approximately parallel to the elongation of the belt of premineral rocks and northeast to east-northeast fractures and dikes.

The northwest-striking Butte fault is the most prominent structure in the district. It can be mapped from the northwestern end of the premineral outcrop as far south as the Lone Star stock and can be traced beneath the alluvium for the rest of the length of the district. It may well extend farther to the southeast to coincide with a conspicuously straight stretch of the Gila River south of Sanchez. The fault dips 65–80° SW. Exposure of premineral rocks are almost entirely restricted to the northeast, upthrown side of the Butte fault, although premineral rocks are known in drill holes and in a few outcrops on the hanging-wall block.

Other northwest-striking faults are known. The Valley fault, together with the Butte fault, forms a graben southwest of the Phelps-Dodge deposit, and the Carpenter fault has offset the quartz monzonite porphyry stock at the Sanchez deposit. The Staghorn and Vulture faults can be mapped in the postmineral volcanic rocks behind the range front. These two faults form a horst that accounts for the very small window of premineral tuff near the center of the Kennecott deposit; they also appear to have controlled the configuration of the oxidized and supergene portions of the deposit. The Vulture fault apparently extends farther to the

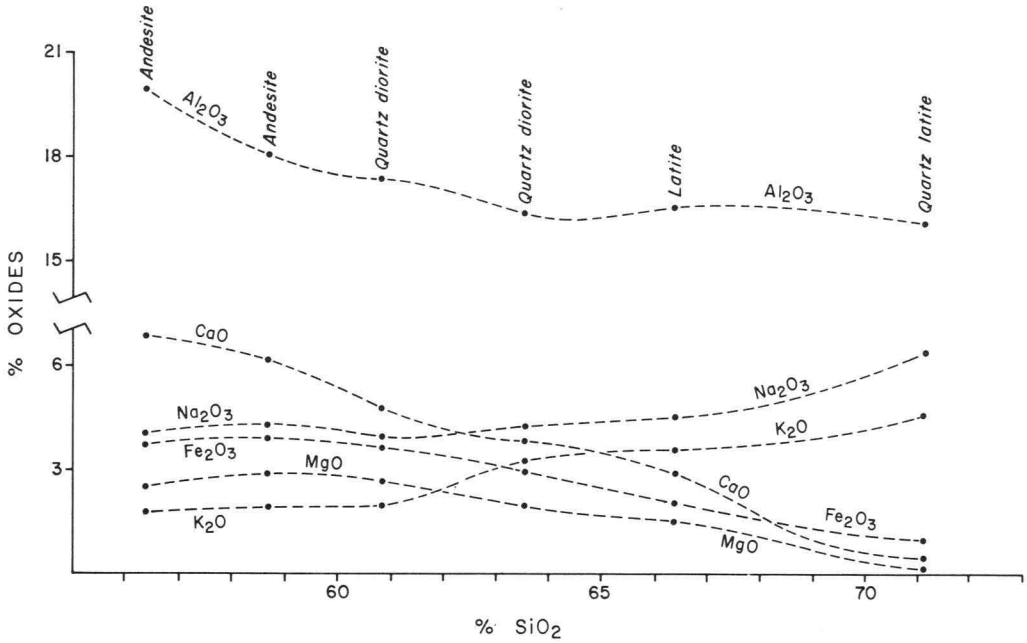

Fig. 4. Variation diagram for Eocene igenous rocks, Safford district

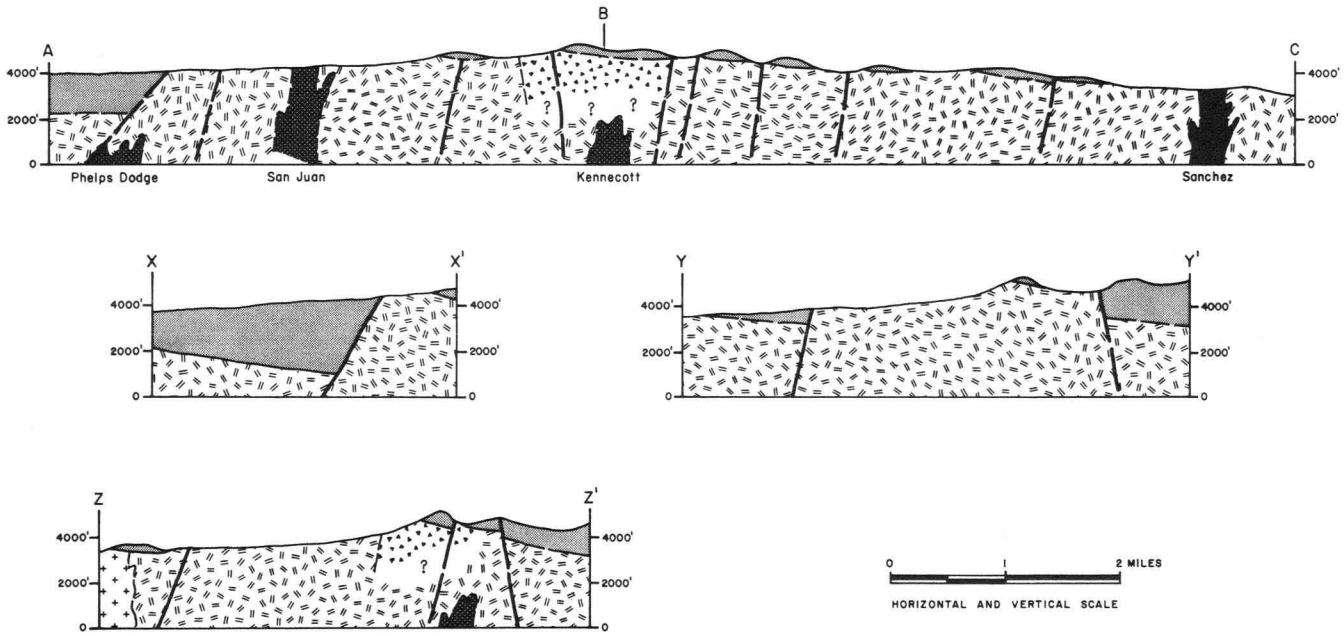

Fig. 3. Cross sections, Safford district

northwest and forms the boundary of the premineral outcrop northeast of the San Juan mine.

The amount of vertical displacement on the northwest-striking faults, all of which cut the postmineral volcanic rocks, is shown on cross sections X-X', Y-Y', and Z-Z' in Figure 3. The depth to premineral rock in each cross section is known accurately from drill holes.

Vertical displacement on the Butte fault ranges from more than 4,000 feet in the northwest to approximately 3,000 feet near the Lone Star stock. Slickensides on the fault plane and lack of drag or displacement of the dikes that are cut by the fault suggest that movement on the Butte fault has been primarily dip-slip. The fault displaces some portion of the Phelps-Dodge sulfide system, however, with an indication of left-lateral displacement. Vertical displacement on the other northwest-striking faults is no more than a few hundred feet. The premineral-postmineral contact marks the maximum measurable vertical displacement; in most of the northwest-striking faults, including the Butte, the displacement of marker units within the postmineral volcanic units is less than the maximum, indicating that the faults were reactivated during the period of postmineral volcanism.

Elongation of the premineral outcrop belt and irregular alignment of quartz monzonite porphyry stocks within the district are both thought to be a reflection of the same regional structures that controlled the northwest-trending faults. This regional structure is presumably an expression of the Gila discontinuity proposed by Titley (1976).

The most prominent structural features at the individual porphyry deposits strike northeast to east-northeast; these features include fractures and dikes, but few faults striking in that direction have been mapped. Stastistical treatment of mineralized fractures in three different areas of the district clearly shows the predominance of the northeast direction (Fig. 5). The Coyote Wash area is the northern end of the premineral outcrop north of the Hackberry fault. This northeast structural direction is a regional feature common in many of the Laramide stocks in Arizona (Rehrig and Heidrick, 1972).

Only a few northeast-trending faults have previously been mapped in the district because of the lack of marker units within the andesite. The Lone Star and Trojan faults were recognized because of obvious offset in the base of the postmineral volcanic cover and this displacement has been only a few hundred feet.

At least four other major northeast-striking faults cut the premineral andesite. These faults are not easily discernible but can be mapped on the basis of the following observations:

1. The Weber Peak fault is indicated by

   a. A very pronounced topographic alignment on both sides of the saddle
   b. Offset of the base of the postmineral volcanic cover.
   c. The straight collinear southeastern margin of the Lone Star stock.

2. The Dry Canyon fault is indicated by

   a. Offset at the base of the postmineral cover.
   b. The abrupt western termination of the window of premineral rocks in the back of the range.
   c. An obvious topographic alignment extending to the northeast.

3. The Solomon Pass fault can be inferred from

   a. A fault repetition of the postmineral tuff at the base of the volcanic cover at the head of the pass.
   b. The existence of the pass itself and a topographic alignment in both directions from the head of the pass.
   c. The straight eastern margin of the small quartz diorite plug east of the Horseshoe mine.

4. The Walnut Springs fault is indicated by

   a. A zone of intense fracturing mapped by Blake just west of the San Juan stock.
   b. The topographic alignment, marked by springs, that extends from the fractured outcrop near the Butte fault to the northern edge of the andesite outcrop.

Another probable northeast-trending structure, the Hackberry fault, occurs at Hackberry Spring and is marked by weak copper oxide mineralization along the bottom of a pronounced linear valley. Several other northeast-trending faults are thought to cut the Safford mining district, but they have not been accurately located.

The Weber Peak, Solomon Pass, and Dry Canyon faults can all be traced for several miles farther to the northeast on aerial photographs. They are parallel to and on strike with similar faults in the Morenci district (Langton, 1972); these faults at Morenci are not thought to be continuations of the Safford faults but again are a reflection of the regional stress field in southern Arizona.

The northeast-striking faults apparently controlled the present location of the porphyry de-

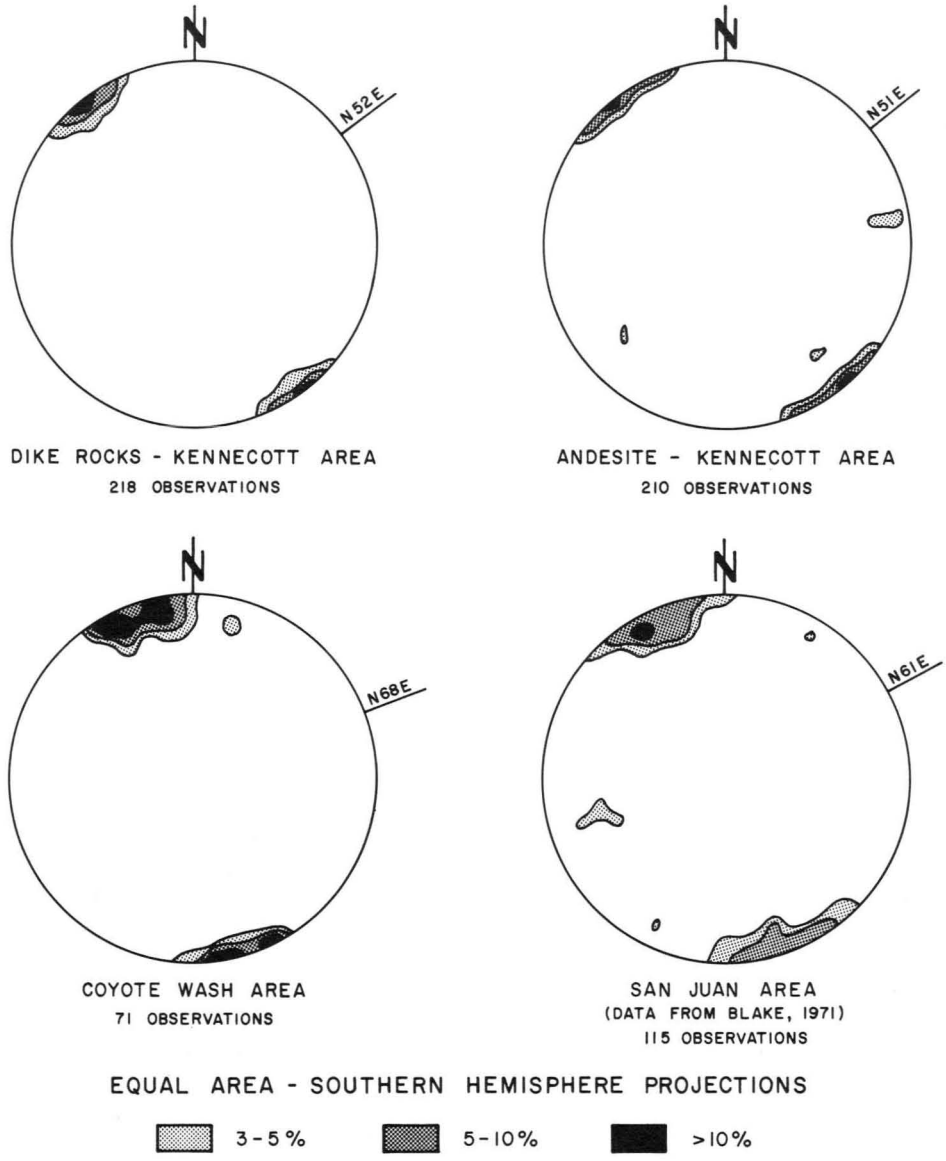

Fig. 5. Poles to mineralized fractures, Safford district

posits—both laterally and vertically. The vertical displacement during Tertiary time along these faults is only a few hundred feet as opposed to the 1,000 feet or more in Morenci. The amount of displacement since the formation of the porphyry copper deposits, however, is thought to be considerably greater than the amount that can be measured by the offset at the base of the postmineral cover. Copper mineralization along the Lone Star, At Ease, and Hackberry faults indicates the early existence of these structures.

The quartz monzonite porphyry stocks at the four porphyry copper deposits in the Safford district are nearly identical in both composition and texture. Assuming that these stocks were originally emplaced at approximately the same elevation, the total vertical separation between the Phelps-Dodge and San Juan deposits and between the Kennecott and San Juan deposits must be a minimum of 2,000 to 2,300 feet (Section A-B-C, Fig. 3). The minimum separation between the Kennecott and Sanchez deposits must be approximately 1,500 feet, and perhaps 1,800 feet, between the Kennecott deposit and the small plug of quartz monzonite porphyry at the Horseshoe mine. These vertical separations have been accounted for by late-Laramide or early-Tertiary movement along the various northeast-trending faults.

This hypothesis, based on the above assumption, is supported by the amount of movement along the Weber Peak fault indicated by the

quartz diorite which is exposed at the surface west of the fault but is encountered only at a depth of about 1,500 feet in drill holes east of the fault. This is the same sense of movement that is indicated by the displacement of the overlying basalts and is suggested by the present elevations of the stocks at the Kennecott and San Juan deposits.

Lateral displacement along the northeast-striking faults cannot be definitely established, although it is suggested in the case of the Lone Star fault by an abrupt change in mineralization across the fault. A deep drill hole southeast of the fault encountered no appreciable sulfide mineralization for its entire length, although it is within 1,000 feet of the Kennecott deposit. Considering the extensive vertical range of mineralization in the sulfide systems in the district, it appears unlikely that such an abrupt change in mineralization can be accounted for by vertical displacement alone. Lateral displacement on some of the northeast-trending faults may therefore account for the lack of strict alignment of the four deposits in the Safford district.

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ALTERATION AND MINERALIZATION OF THE CYPRUS JOHNSON DEPOSIT, COCHISE COUNTY, ARIZONA

by

R. L. Clayton[1]

Abstract

The Johnson mineralized area is on the northeast side of the Little Dragoon Mountains in southeast Arizona. Initial mining by Cyprus Mines Corporation (1942-1957) centered on metasomatic massive sulfide deposits largely confined to the middle member of the Cambrian Abrigo Formation. Currently a stratigraphically controlled secondary copper oxide deposit in the lower member of this formation is being mined by open-pit methods.

Rocks of the area are of Precambrian to Holocene age, but the bulk of the economic minerals occurs as skarn deposits in Paleozoic rocks, which lie in a slightly undulating monocline striking northwest and dipping 40° NE. The Paleozoic sedimentary rocks were metasomatically altered by intrusion of the 53-m.y. Texas Canyon quartz monzonite, a barren stock characterized by K-feldspar phenocrysts. Wherever the east side of this stock protrudes into the sedimentary rocks, a mineral deposit has been found adjacent to or in line with the protrusion (Johnson, I-10, Strong & Harris, and Dragoon deposits).

Two phases of a single alteration process are evident: metamorphism of impure carbonate rocks to silicate rocks and metasomatism in which potassium, base metals, sulfur, etc. were added by way of quartz veins. The lower Abrigo hornfels has been pervasively invaded by mineralized quartz veins. About 30 percent enrichment has resulted from supergene processes; oxidation of secondary chalcocite and primary chalcopyrite produced an economic mining grade. The impervious underlying Bolsa Quartzite confined the secondary solutions to the hornfels. The principal ore minerals are chrysocolla, malachite, azurite, and tenorite(?).

Conjugate fault systems and intrusion of the stock resulted in massive fracture of the lower Abrigo hornfels at Johnson, creating a particularly amenable host for quartz veining and secondary leaching processes.

Introduction

The Johnson district is in the Dragoon quadrangle in northwestern Cochise County, Arizona, 60 miles east of Tucson via Interstate 10 (Fig. 1). Initial mining (1942-1957) by Cyprus Mines Corporation was centered around metasomatic massive sulfide (chalcopyrite, sphalerite, and pyrite) replacement deposits largely confined to the middle member of the Cambrian Abrigo formation. Currently, a stratigraphically controlled secondary copper oxide deposit in the lower member of the Abrigo Formation is being mined by open-pit methods. The present phase of mining is designed to process 22 million tons of oxide ore having a grade of 0.85% total copper.

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The rock formations of the area include early Precambrian, late Precambrian, Paleozoic, Mesozoic, Tertiary, and Quaternary units. Table 1 is a generalized stratigraphic section at Johnson (Cooper and Silver, 1964).

The bulk of the economic minerals occurs in skarn within the Paleozoic sedimentary rocks. These rocks lie in a slightly undulating monocline striking northwest and dipping 30°-40° NE. (Fig. 2). They have been altered by the metamorphism and metasomatism associated with the intrusion of the Texas Canyon quartz monzonite stock.

The Texas Canyon Quartz Monzonite Stock

The stock is a biotite quartz monzonite displaying potassic feldspar phenocrysts 2-5 cm long. An alteration phase, largely confined

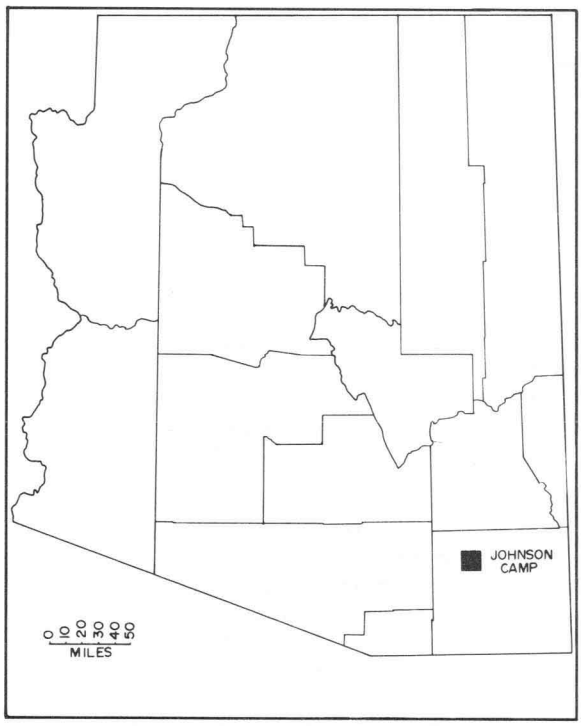

Fig. 1. Index map of Arizona

to the northeast periphery of the stock, is characterized by multiple quartz veining, which is sometimes tungsten bearing. Surrounding the quartz veins are two zones of alteration: (1) a hard inner zone, usually only a few centimeters wide, containing varying amounts of muscovite, silica, and pyrite, and (2) a wider outer zone displaying only weak argillic alteration (Cooper and Silver, 1964). The stock is early Tertiary in age, 53 m.y. (Livingston and others, 1967), elongate to the northeast, and occupies an area of roughly 4 x 7 miles.

The stock is generally concordant with the steeply dipping Pinal Schist and discordant with the post-Pinal rocks. The most prominent joint attitude measured by Cooper and Silver (1964) is N. 45°E., dipping 86°SE., with less well defined attitudes of N. 5°W., dipping 65°W., and N. 75°W., dipping 85°S. They suggest that the stock has a gently arched roof, the northeast extension of which lies under Johnson at moderate depth. Evidence for this conclusion is:

1. The intense igneous metamorphism near the Johnson deposit as much as 1.5 miles from the exposed contact.

2. The occurrence of tremolite in the Glance Conglomerate at the north end of the Gunnison Hills, as much as 3 miles from the exposed stock.

Kantor (1975) offers an interesting variation to the eastward extension of the stock. He theorizes that a portion of the stock intruded above the altered and mineralized zones at the Johnson deposit for a distance of at least 2 miles. Hence, mineralization and alteration were downdip rather updip phenomena. His arguments for this reasoning are:

1. The great horizontal extent of the copper-zinc mineralization and calc-silicate tactitization relative to the short vertical or downdip extent.

2. The relatively uniform dip to the base of the alteration and mineralization.

3. The fact that no drill holes or mine workings in the district ever penetrated the stock below the Paleozoic rocks.

It is interesting to note that on the northeast side of the stock, its protrusive character is a harbinger or indicator of mineralization. The Johnson, I-10, and Dragoon deposits are all closely associated with discordance of the stock with the post-Pinal sedimentary rocks.

Metamorphism

The Johnson deposit falls within Cooper's alteration zone 4 (Cooper, 1957), which is characterized by marbleization of the pure dolomites and limestones. The impure dolomites have been altered to forsterite, diopside, tremolite with or without calcite, while the impure limestones were altered to garnet, diopside, epidote, wollastonite, and idocrase. The shale of the lower Abrigo has been altered to a biotite hornfels.

The following is a brief comparison of the altered Paleozoic sedimentary rocks in the immediate vicinity of the Johnson deposit with their unaltered equivalents in the Dragoon Mountains as described by Cooper and Silver (1964).

Martin Formation

The Martin Formation has an upper 30-foot unit of dolomitic shale and siltstone overlying 1 to 3-foot beds of dolomite and sandy or silty dolomite. The top shale unit has been altered to a hornstone, which consists of diopside-hedenbergite and lesser tremolite with interstitial K-feldspar and quartz. The clean dolomites have been dedolomitized to diopside-tremolite-calcite rock and locally to tremolite-forsterite-calcite rock in a groundmass of variable quartz and K-feldspar. In the field, these rocks are called tactites.

Table 1. Generalized section at Johnson

Age	Group, Formation, or Member	Thickness, ft
Tertiary and Quaternary		0-1500+
	Unconformity	
Tertiary	Texas Canyon Quartz Monzonite	
	Unconformity	
Pennsylvanian	Horquilla Limestone	1600
Pennsylvanian or Mississippian	Black Prince Limestone	125
Mississippian	Escabrosa Limestone	650
Devonian	Martin Formation	200
Cambrian	Abrigo Formation	
	Upper Abrigo dolomite	100-120
	Middle Abrigo limestone	150-200
	Lower Abrigo limestone	250-300
	Bolsa Quartzite	50-100
	Unconformity	
Upper Precambrian	Apache Group	
	Diabase	
	Dripping Spring Quartzite	100-150
	Barnes Conglomerate	5
	Pioneer Shale	300
	Scanlan Conglomerate	2
	Unconformity	
Lower Precambrian	Pinal Schist	5000+

Abrigo Formation

Upper Abrigo. The upper Abrigo has a quartzite upper bed followed by 6 to 12 inches of interbedded dolomitic sandstone and sandy dolomite. These dirty dolomites alter to a diopside-tremolite-calcite rock with a groundmass of variable quartz and K-feldspar. Again, in the field these rocks are frequently referred to as tactites or white tactites.

Middle Abrigo. The middle Abrigo is a crenulated limestone with intercalated limy sand and shale partings 0.3-2.5 cm thick. These partings increase in frequency with depth thereby forming a gradational contact with the lower Abrigo shale. Under metamorphic conditions, the limestones alter to predominantly garnet with lesser diopside, quartz, and calcite. The intercalated shale partings alter to a hornfels consisting of biotite and feldspar with small amounts of quartz, sphene, epidote, and apatite. In places, both the limestone and shale units have been garnetized. Unit 5 at the top of this member of the Abrigo Formation has been strongly garnetized, frequently in well-defined shoots at fold crests, and has accounted for 95 percent of the pyrometasomatic copper-zinc replacement deposits in the district.

Lower Abrigo. The lower Abrigo is a gray fissile shale with intercalated carbonate and quartzite beds. The carbonates are dolomite near the base and limestone near the top.

The shale has been altered to a biotite hornfels that consists of biotite with variable K-feldspar and lesser quartz, epidote, sphene, and chlorite. The minor carbonate interbeds have been altered to bands of epidote, diopside, tremolite, and calcite. The quartzite

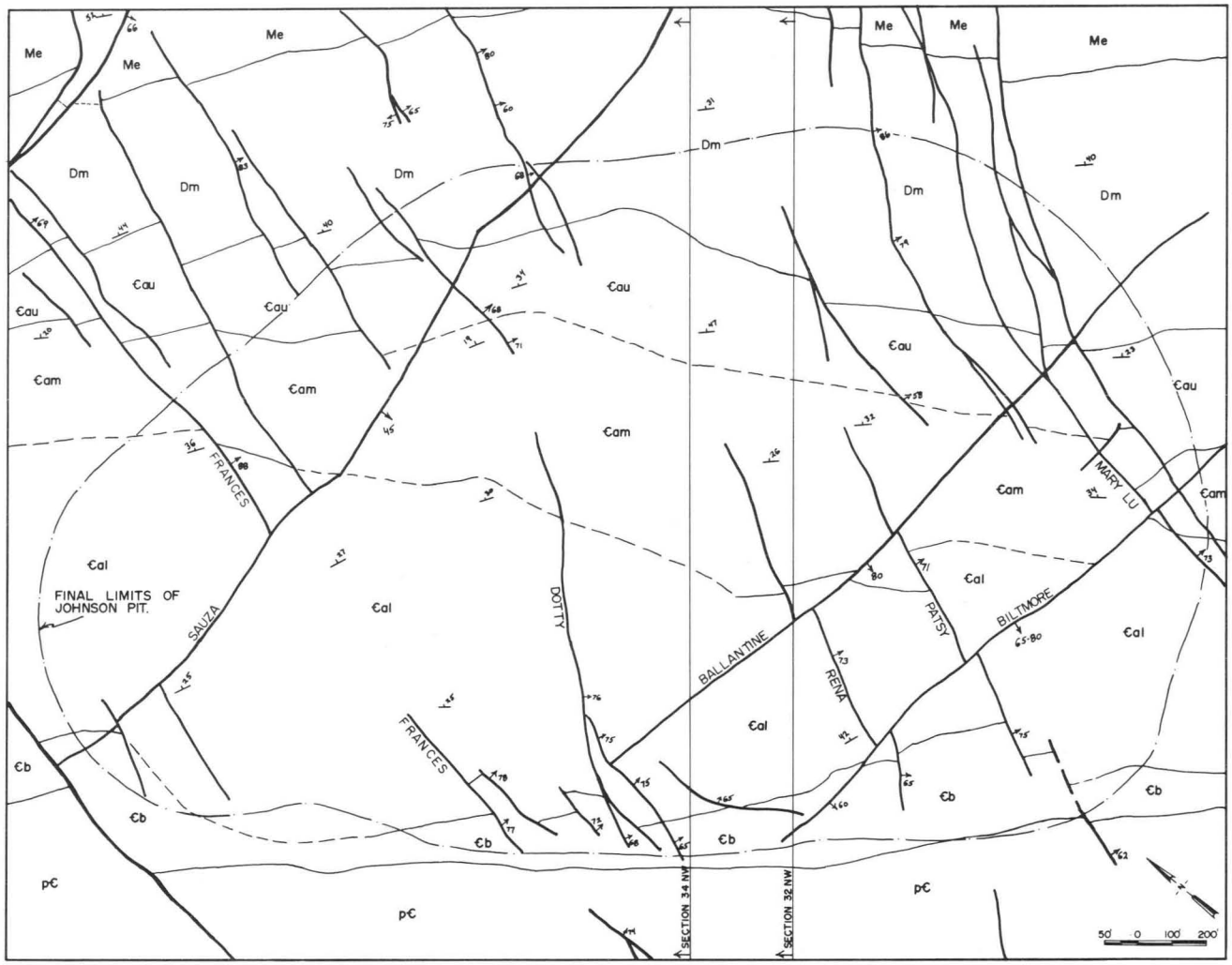

Fig. 2. Surface geology at the Johnson pit. Me = Escabrosa, Dm = Martin, Єam = middle Abrigo, Єal = lower Abrigo, Єb = Bolsa, pЄ = Apache.

bands, usually rich in K-feldspar, may be partially altered to garnet-diopside or epidote-diopside assemblages.

This member of the Abrigo formation is currently being mined for its copper oxide content.

Bolsa Quartzite

The Bolsa Quartzite has not been appreciably affected by the metamorphism. Studies made by Cooper (1957) and Baker (1952) suggest that most of the above-described metamorphism involved reactions between the original constituents of the beds. Migration was probably limited to adjacent beds in a medium of liberated carbon dioxide. Little, if any, material, except possibly water, was added to the system.

Metasomatism

Most metasomatic alteration took place later and at lower temperature than the metamorphism of the host rocks (Baker, 1952). The most striking effect of the metasomatism was, of course, the copper-zinc mineralization associated with the replacement deposits of the middle Abrigo and the mineralization presently being mined in the lower Abrigo. Late manganiferous garnet rims indicate some manganese metasomatism (Baker, 1952).

Cooper (1957) found that the unmetamorphosed Abrigo Formation contains 20-25 percent and, in some cases, 50 percent detrital and authigenic K-feldspar in all parts of the Little Dragoon Mountains. He therefore believes that potassium metasomatism was rel-

atively minor and was confined to the transfer of potassium between beds through defeldspathization.

However, the appreciable K-feldspar in the quartz veins and the alteration of the diabase, which underlies the Dripping Spring Quartzite, to a magnetite-biotite-orthoclase hornfels containing 50%-60% K-feldspar, 25%-30% biotite, and 5%-10% magnetite suggest fairly widespread potassium metasomatism.

Other common late alteration products frequently associated with small amounts of sulfides are calcite, quartz, ferrotremolite, chlorite, and fluorite.

Structure

Baker (1952) recognized three sets of faults during his underground studies of the copper-zinc replacement deposits: Northeasters, Easters, and Northwesters. This fault system has been further defined in the pit area by diamond drilling and pit mapping (Figs. 2 and 3).

The Northeasters are the most numerous and best developed set. They strike N. 10°-30° E. and dip 70°-75° SE. They are normal faults with apparent right-lateral displacement of the beds. The faults are commonly quartz-filled veins that contain K-feldspar, fluorite, calcite, and sulfides. The Northeasters are usually offset by other faults but the reverse relationship is also true. The Northeasters, serving as channelways, were instrumental in the formation of the replacement orebodies of the middle Abrigo (Baker, 1952).

The Easters range in strike from N. 60° E. to S. 60° E. They consist of a low-angle set of normal faults, which dip 30°-50° S. and a high-angle set of reverse faults, which dip 75° S. The Republic and Sauza are the two most prominent low-angle Easters in the pit area, while the Ballantine and Biltmore are the prominent high-angle reverse Easters (Fig. 3).

The Northwesters are relatively rarer than Northeasters and Easters. They strike N. 15° W. and dip steeply either east or west.

Structural analysis by stereographic projection indicates that initial faulting began while the beds were still horizontal prior to Late Cretaceous tilting to the northeast and intrusion of the Texas Canyon stock. This early conjugate fault system consisted of east-dipping Northwesters, Northeasters, and steeply dipping Easters, which were then normal faults dipping north. During or after tilting, another conjugate system developed consisting of west-dipping Northwesters, Northeasters, and low-angle Easters. Later movement of the entire system probably occurred during intrusion of the Texas Canyon stock.

Mineralization

Primary Mineralization of the Lower Abrigo

The lower member of the Abrigo Formation has been massively fractured by the above-described fault system. These faults and fractures are the sites for the late mineralized quartz veins that pervade the hornfels.

Cooper and Silver (1964) and Baker (1952) limit these metasomatically introduced quartz veins to the Northeast fault system. Pit studies, however, indicate that the vein fillings are polydirectional, but the bedding-plane orientation is predominant. The veins are commonly less than 3 cm but are rarely as much as 60 cm wide.

Quartz, feldspar, and occasionally calcite constitute the chief vein material. Of the primary sulfide mineralization, pyrite is the most abundant and widespread, with much less chalcopyrite. Galena, molybdenite, bornite, and tetrahedrite have also been rarely noted. Commonly, the sulfides occur as open-space fillings. Other primary minerals found in the quartz veins are magnetite, hematite, fluorite, scheelite, and wolframite.

In addition to the mineralized quartz veins, there is disseminated pyrite and lesser chalcopyrite. However, the bulk of the mineralization is quartz vein dependent; even the disseminated sulfides increase with the intensity of the quartz veining.

Secondary Mineralization

Oxidation has been stratigraphically controlled by the channeling of the secondary solutions downdip through the massively fractured lower Abrigo. This channeling was controlled by the overlying tactite beds and more importantly by the impermeable underlying Bolsa Quartzite, which guided the secondary solutions downdip, and the Bolsa is now the footwall of the orebody and the contact is a horizon of high copper values (Fig. 4). Structurally high Bolsa Quartzite at the northwest and southeast ends of the pit has formed a trough of quartzite that contains the bulk of the deposit.

The downdip limit of the oxide portion of the deposit is the Sauza fault, which has apparently produced an impervious barrier for the secondary solutions (Fig. 4).

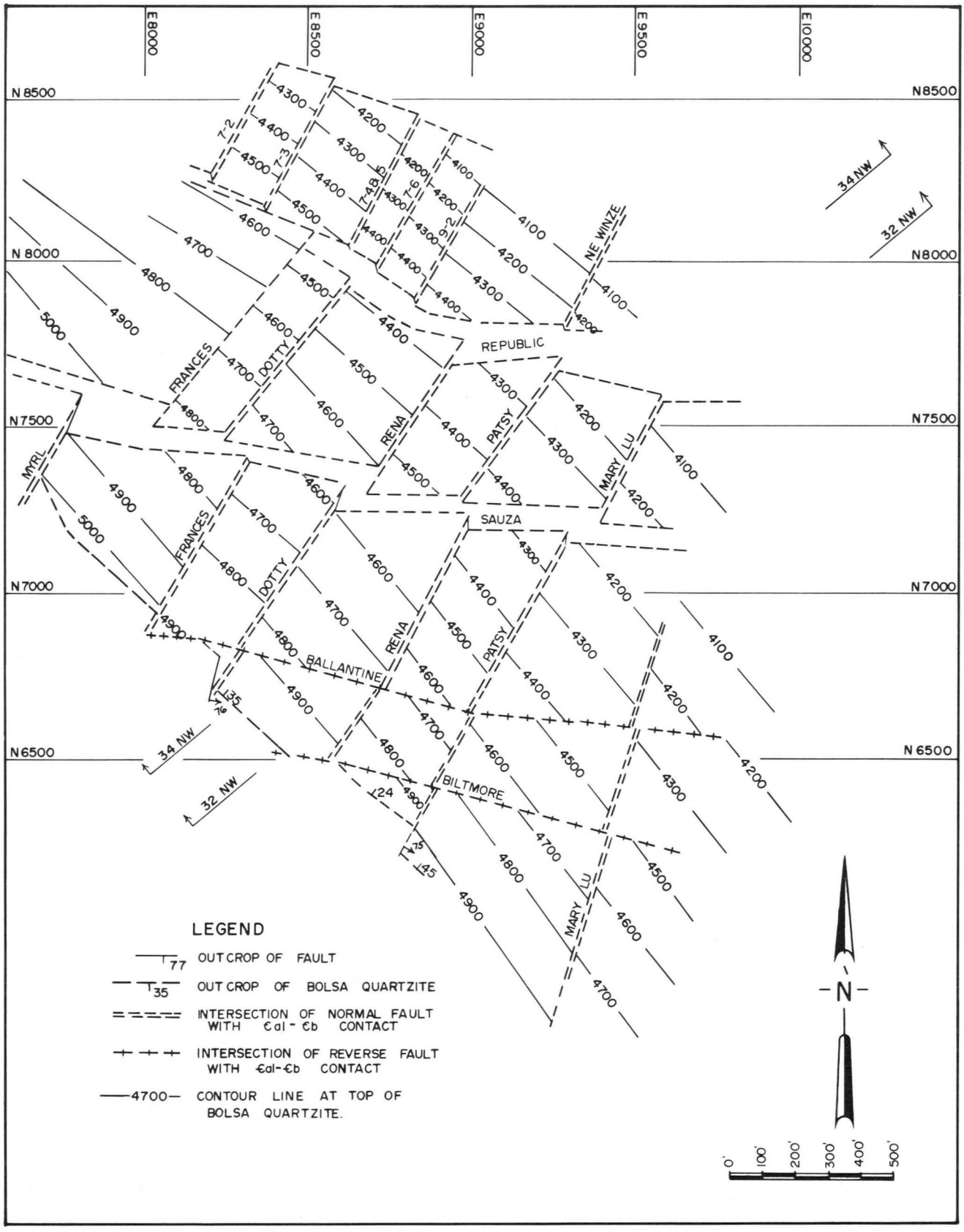

Fig. 3. Structural contour map of the lower Abrigo—Bolsa contact

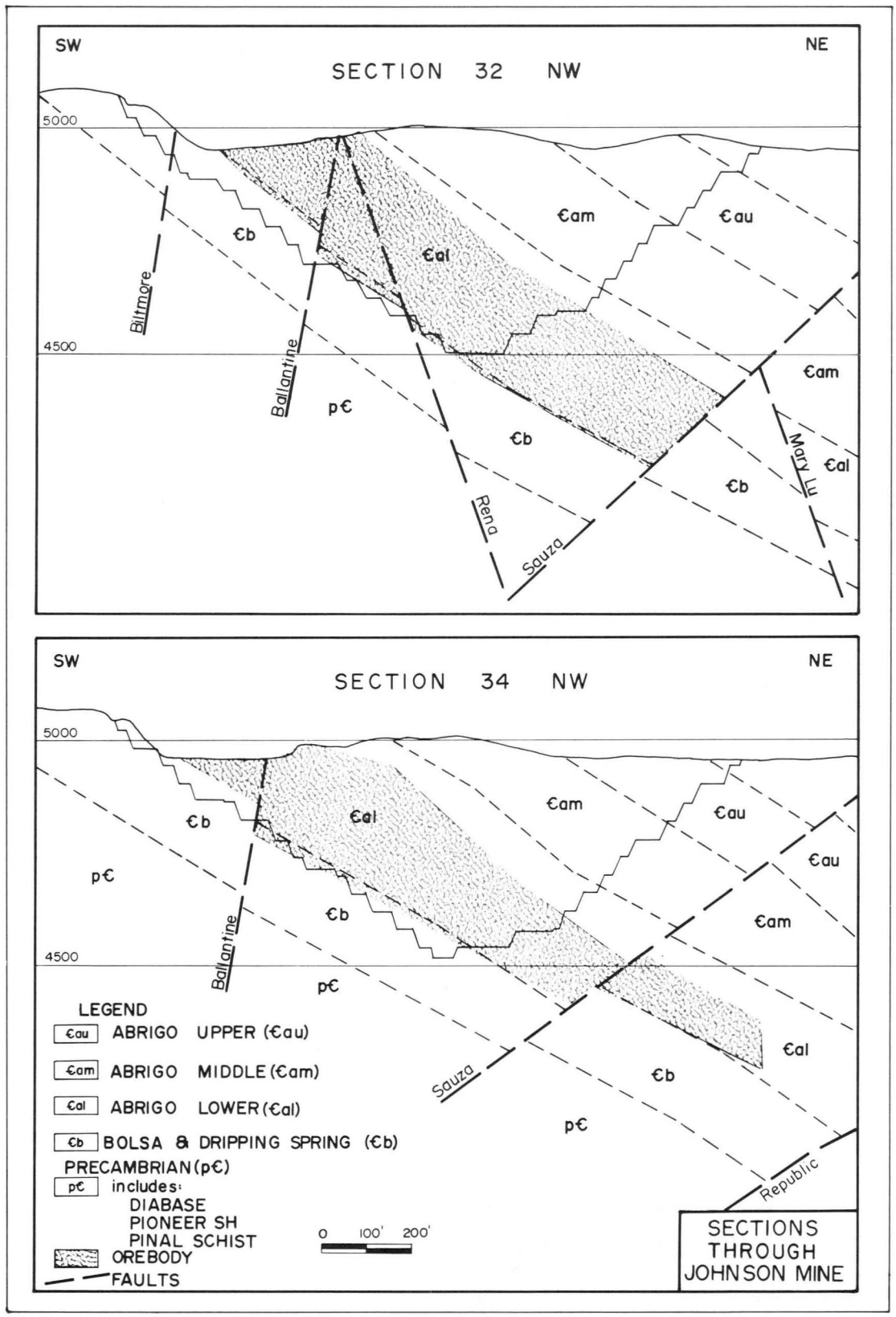

Fig. 4. Sections through Johnson mine, looking northwest

The principal secondary copper oxide is chrysocolla, but other common oxides are tenorite(?), malachite, and azurite. Rarer oxides include aurichalcite, chalcotrichite, and unidentified copper oxides. Most copper oxides occur in fractures.

Abundant montmorillonite and lesser kaolinite are the chief secondary argillaceous products of the oxide zone. Indigenous limonite-goethite, hematite, and jarosite are characteristic of all quartz veins and are frequently associated with casts and boxworks. Pyrolusite and psilomelane occur in some fractures of the host.

Secondary Enriched Zone

There was appreciable interpenetration between the oxide zone and the secondary enriched zone, but some chalcocite commonly appears at about 500 feet. The enrichment is quite weak and frequently nothing more than paint on the primary sulfides. The average enrichment appears to be about 30 percent.

The values gradually decrease downdip to 0.1-0.4% copper. The deepest hole intersected the lower Abrigo 1,700 feet downdip and these values were still holding. However, the presence of chalcocite indicates that the true primary values have not been intersected.

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THE GEOLOGY OF THE COPPER CREEK AREA, BUNKER HILL MINING DISTRICT, GALIURO MOUNTAINS, ARIZONA

by

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Abstract

Copper Creek is located 14 miles northeast of San Manuel on the western slope of the north-central Galiuro Mountains in the Bunker Hill mining district, Arizona. Copper Creek is important in understanding the porphyry copper system because it furnishes the chance to study the upper-level occurrence of a deep mineralized porphyry copper deposit.

Minor outcrops of Precambrian and Paleozoic sedimentary rocks are found in the eastern and northeastern portions of the district. In the north, west, and south portions is a thick heterogeneous sequence of andesitic and dacitic volcanic rocks designated as Cretaceous(?) Glory Hole Volcanics. Intrusive into these older rocks are three stocks of Copper Creek granodiorite and associated porphyries. Overlying the intrusive rocks are the Galiuro Volcanics, a thick sequence of Tertiary flows, tuffs, and agglomerate. Plio-Pleistocene Gila Conglomerate is in fault contact with the older rocks along the western edge of the district. The Copper Creek stocks consist of an equigranular phase (Copper Creek granodiorite) and a porphyritic phase (dacite porphyry). The porphyritic phase is divided into pink porphyry, feldspar porphyry, and dark porphyry varieties.

The principal structural trends are east-northeast, northwest, and north, expressed by fracturing, veins, faults, and the shapes and alignment of the intrusions and breccias.

Spacially and chronologically associated with the dacite porphyry are breccia pipes. Gensis of the breccias is closely linked with emplacement of the dacite porphyry stocks. Intersecting structures localize and control the emplacement of the porphyries and the shapes of the breccias.

Significant porphyry copper mineralization is present in the American Eagle basin located in the south-central portion of Copper Creek. The copper mineralization occurs 2,000 feet or more below the surface in an area of relatively intense veining and clusters of breccia pipes and dacite porphyry plugs. The deposit is a low-sulfide system averaging approximately 3 percent by weight total sulfides. In the upper portions, the sulfide is predominantly pyrite, which grades downward into the predominantly chalcopyrite zone. Bornite and some molybdenite occur at the base and below this zone. The mineralization shows strong fracture and breccia control throughout the system.

Zones of pervasive alteration are not well defined at Copper Creek. In the American Eagle basin sericite is the dominant alteration product. It is associated with the breccia pipes, veins, and many of the dacite porphyry plugs. Potassic and argillic alteration occur as scattered zones, along with lesser amounts of tourmalinization, silicification, and propylitization.

Introduction

Copper Creek, located on the western flank of the north-central Galiuro Mountains, 50 miles north-northeast of Tucson, Arizona, is part of the Bunker Hill mining district. History of exploration and mining activity at Copper Creek began in 1863 with the first recording of mining claims. First mining was for lead and silver at the Blue Bird mine. In 1883, the Bunker Hill mining district was organized and recorded. The first copper exploration began with the Table Mountain Copper Company in

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1897-98. From 1903-1917 prospecting and some production was done at the Old Reliable and other breccia pipes by the Copper Creek Mining Company. The Calumet and Arizona Mining Company did exploration work in northwest Copper Creek from 1907 to 1909. In 1933 the Arizona Molybdenum Corporation obtained the Childs-Aldwinkle mine, which produced until 1938, when mining activity in the district ceased. During this time, total known metal production was over 8 million pounds copper, nearly 7 million pounds molybdenite, over 4 million pounds lead, and in excess of 200,000 ounces silver and 726 ounces gold.

Early copper exploration efforts in the Bunker Hill mining district were concentrated on the mineralized breccia pipes. The first exploration for a porphyry copper-type deposit by deep drilling was done during the middle 1960s by Bear Creek Exploration. Newmont began its exploration effort at Copper Creek in 1966 and was joined in 1971 by Exxon.

Geologic work in and adjacent to the Copper Creek area was done by Kuhn (1941), Creasy, Jackson, and Gulbrandsen (1961), Simons (1964), and Krieger (1968). Information on individual mines or breccia pipes was published by Weed (1913), Kuhn (1938), Denton (1947), Joralemon (1952), and Simons (1964).

Geology

Figure 1 shows the general geology of the Copper Creek area. The Galiuro Mountains are a north-northwest-trending, elongate range along the eastern edge of the San Pedro Valley and are formed mostly of gently east-dipping Tertiary volcanic rocks. Pre-Tertiary rocks underlying the volcanics are exposed along the northwestern flank of the Galiuro Mountains. Copper Creek Canyon cuts into and across the southern portion of these older rocks exposing Precambrian and Paleozoic sedimentary rocks and Mesozoic to lower Tertiary volcanic and intrusive rocks. Plio-Pleistocene semi-consolidated fanglomerate is in fault contact with the western edge of the district.

Pre-intrusive Rocks

Exposures of pre-intrusive rocks occur in the eastern portions of the district. Precambrian Apache Group sedimentary rocks (Dripping Spring Quartzite and Mescal Limestone) with basal Paleozoic sedimentary rocks (Bolsa Quartzite) are found in the southeastern portion. This block of north-south-striking, moderately west dipping units is covered by volcanics to the east and south and is intruded on the north and west. In the east and northeast are broadly folded Paleozoic rocks (Bolsa Quartzite, Martin Formation, Escabrosa Limestone) and Mesozoic rocks (Pinkard Formation). Volcanic rocks overlie them to the north and east and intrusive rocks cut the exposures to the west and south.

Much of the western half and part of the southern edge of the mapped istrict is Cretaceous(?) Glory Hole Volcanics. This rock group comprises a heterogeneous pile of andesitic to latitic tuffs, welded tuffs, breccias, lavas, and flow breccias. They lie unconformably on Paleozoic and Precambrian sedimentary rocks and are overlain by Tertiary volcanics. Thickness of the volcanics is unknown. Thermal metamorphism from adjacent intrusive stocks has strongly modified the volcanic rocks into a dark-gray to black, dense, very fine grained, crystalloblastic-hornfelsic rock. Only on weathered surfaces are the primary volcanic textures sometimes visible. Relict flow features, occasional interbedded lenses of quartzite, and minor fresh-water limestones suggest that the volcanics strike northwest and dip gently to the northeast.

Intrusive Rocks

The Copper Creek granodiorite and associated porphyries intrude the older sedimentary and volcanic rocks. The Copper Creek granodiorite occurs in three northwesterly aligned stocks: the northwest Dry Camp stock, the central Copper Creek stock, and the southern Sombrero Butte stock. Much of the eastern half of the mapped area is the Copper Creek stock.

Copper Creek granodiorite is gray to light gray, medium to fine grained, hypidiomorphic-granular to slightly porphyritic. It consists of 5 to 20 percent orthoclase, 40 to 50 percent plagioclase, 15 to 20 percent quartz, and 5 to 6 percent biotite. Hornblende is occasionally present but is generally replaced by biotite.

Porphyritic intrusive rocks occur as plugs and dikes and are generally clustered within three northwest-trending zones (eastern, central, and western portions of the area). They intrude all previously described rocks. Petrographically, the porphyries have been grouped into diorite porphyry and dacite porphyry. The diorite porphyry is dark gray and consists of fine-grained plagioclase, hornblende, and minor quartz. This rock type is not common and may represent an earlier phase of the granodiorite.

The dacite porphyry group has been divided into three subtypes based on field classification: pink porphyry (eastern porphyry zone and partially in southern portion of central zone);

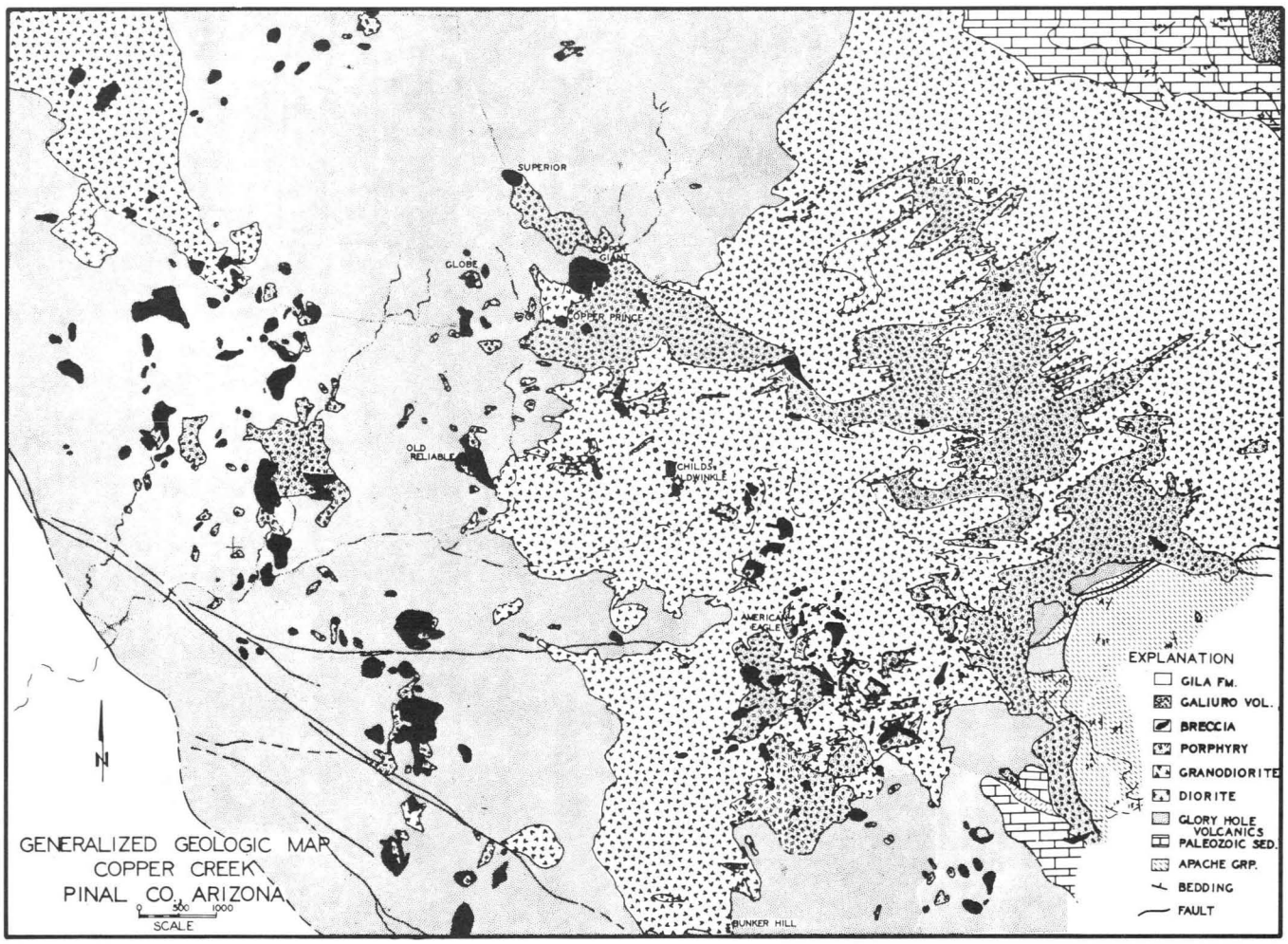

Fig. 1. Generalized geologic map, Copper Creek, Pinal County, Arizona

feldspar porphyry (central zone); and dark porphyry (western zone, 60 percent southern portion of central zone, and less than 5 percent of eastern zone).

Pink porphyry is light pink and has a quartz monzonite composition. It is composed of medium-grained plagioclase (10-15%) and minor biotite (less than 5%) phenocrysts set in a fine-grained, aplitic matrix of quartz and orthoclase.

Feldspar porphyry is gray and has a granodiorite composition. Mineralogically, the porphyry comprises 50 to 65 percent medium-grained plagioclase, up to 5 percent biotite, and occasional rounded quartz phenocrysts set in a fine-grained, xenomorphic groundmass of orthoclase, plagioclase, and quartz. The plagioclase phenocrysts are blocky and somewhat crowded.

The dark porphyry is gray to dark gray and varies from near quartz diorite to granodiorite. Medium-grained phenocrysts of plagioclase (10 to 30%), biotite (5%), and rare rounded quartz are set in a fine- to very fine grained, xenomorphic to felty matrix of plagioclase, quartz, biotite, and orthoclase.

These rocks have been dated by the K-Ar method using biotite. The dates are: granodiorite, 64-68 m.y.; pink porphyry, 59-62 m.y.; and dark porphyry, 52-53 m.y.

Breccia Pipes

Numerous vuggy, highly altered breccias are adjacent to or involved with the dacite porphyries of Copper Creek. These masses have been given the general term "breccia pipes" as several are known to have a near-vertical long dimension. The most common dacite porphyry variety associated with a breccia pipe is dark porphyry. Feldspar porphyry has some breccias associated, but there is none known with the pink porphyry.

Breccia pipes range in size from a few tens of feet to over 600 feet and vary in plan from equant to elongate to irregular. Underground mapping and limited drill data indicate the third dimension of some of them. Shapes indicated are (1) carrot-shaped—breccia flaring upward and tapering downward; (2) two or more aligned breccias coalescing into a single pipe with depth; (3) breccia pinching out into a vein in less than 1,000 feet; and (4) location of lensoid, sheetlike breccia bodies along steep or flat fractures or contacts. Cross sections constructed from drill data, along with surface mapping suggest that some breccias are persistent to over 3,000 feet in depth and that others do not reach the present surface but are blind pipes.

Breccia pipes consist of pebble- to cobble-size, angular to subangular to locally rounded fragments derived from the surrounding wall rock. There appears to be no or very little mixing of rock types. Fragments can vary greatly in size, shape, and texture within a single breccia mass. A zone of well-rounded fragments can occur within a matrix of angular to subangular fragments. Often very large, unbroken blocks up to 100 feet are found surrounded by pebble- to cobble-size fragments. Sometimes the fragments are platy or oblong and are aligned such that a crude layering is apparent. This layering may be interior to the breccia or subparallel to its walls.

Fragments vary from completely altered to quartz-sericite to having a thin rim of quartz-sericite. These fragments can be tightly packed such that intrafragmental areas are absent or minor. Packing in other breccias may be such that large, vuggy areas exist. Intrafragmental areas may be completely filled or may have only minor material present. Quartz-sericite and crystalline quartz are common intrafragmental material. Other materials are tourmaline, pyrite, chalcopyrite, specularite, quartz-orthoclase, and coarse biotite. They may occur separately or in various combinations. The nature of the original intrafragmental filling is unknown.

Contacts between breccia pipes and wall rock are often sharp and generally steep. Wall rock at the contact may exhibit 2-10 feet of closely spaced fractures parallel to the contact or a 1- to 3-foot zone of strongly crushed and moderately altered rock. Alteration of the surrounding wall rock may be limited to a few feet or may extend tens of feet beyond the breccia contact.

Formation of a breccia pipe is associated with the dacite porphyry intrusive rock, based on their close spacial and temporal relationships. Jointing has influenced the location and shapes of the intrusive and breccia bodies. Where several joint sets intersect, a zone of weakness is produced. These zones act as conduits for the emplacement of porphyry plugs and dikes, and forces generated during emplacement cause intense fracturing and brecciation adjacent to and above the porphyry body. These areas of intense fracturing serve as channelways for hydrothermal solutions, which can enhance the breccia texture through alteration and leaching of the fragments. Collapse and additional development of the column of brecciated rock could be promoted through other possible mechanisms, e.g., magma pressure fluctuations, repeated porphyry intrusions, or volume reduction of porphyry by water loss and crystallization. The formation of breccia pipes may result from a number of interrelated processes, and the internal variations between individual breccias only reflect the degree to which a single mechanism functioned during development.

Overlying all previously discussed rocks are the Miocene Galiuro Volcanics. They occur north, east, and south of the area and consist of several thousand feet of andesitic and rhyolitic welded tuffs, flow, ash tuffs, and agglomerates (Simons, 1964; Krieger, 1968). The Plio-Pleistocene Gila Conglomerate is mapped along the western edge of the area. This unit has been faulted down to the west against the older crystalline rocks.

Structure

Joints and veins are the principal structural features mapped. Foliation within the intrusions is almost absent. Rose diagram plots of steeply dipping joints and veins exhibit two major directions, S. 85° E. to N. 70° E. and N. 0° E. to N. 15° W., and two lesser directions, N. 20° W. to N. 55° W. and N. 15° E. to N. 40° E. Flat joints are common at various places in the district. Veining occurs almost wholly in the east-west structural direction. Intrusion and breccia shapes and alignments often exhibit the influence of one or more of these structural directions.

Alteration

A deep porphyry copper system occurs beneath the American Eagle basin. This basin is a topographic feature just south of Copper Creek and is located in the south-central portion of the area. Study of mineralization and alteration of this porphyry copper system is still in its preliminary stages. However, it is apparent that this deposit is a relatively high level, possibly vented porphyry system. Main evidence for shallow emplacement is the abundant breccia pipes and lack of well-defined pervasive alteration zones.

Well-developed, pervasive alteration patterns are not easily recognized on the surface at Copper Creek. Much of the alteration is confined to vein selvages, breccia pipes, and dacite porphyry plugs and their margins. However, some alteration aspects for the different rock types can be generalized. In the Precambrian and Paleozoic sedimentary rocks, the carbonate rocks exhibit the greatest effect. They are mostly recrystallized, with some local argillization and limited calc-silicate development. The Glory Hole Volcanics exhibit pervasive propylitic alteration and silicification with abundant pyrite, especially adjacent to vein sets and where intruded by a cluster of dacite porphyry plugs. Weak, pervasive propylitic alteration with local areas of superimposed potassic and phyllic alteration is common for the granodiorite. Dacite porphyry shows weak to strong phyllic alteration. Very strong phyllic alteration with silicification and local tourmalinization is exhibited by most breccia pipes.

In the American Eagle basin, the rocks contain higher sericite and quartz and lower total feldspar than rocks outside the area. Potassic alteration occurs primarily as the addition of orthoclase by veinlets, vein selvages, or metasomatic replacement. At the surface, potassic alteration is spotty. However, the amount of potassic alteration increases with depth below the basin and a "floor" of fairly intense pervasive potassic alteration underlies the zone of copper-rich mineralization.

Phyllic alteration predominates at the surface in the American Eagle basin. It is confined to vein selvages, breccia pipes and some of the dacite porphyry plugs and their margins; vein selvages are the most common and exhibit well-developed zoning. Quartz-sericite typically borders the quartz-sulfide veinlet. This assemblage grades outward to a quartz-sericite-chlorite zone and to an outer zone of sericite-argillite. This outer zone is characterized by the presence of cloudy to waxy, light-green plagioclase. The alteration product is a mixed mica comprised of sericite, montmorillonite, kaolinite, and illite. With depth the phyllic alteration decreases due to the diminishing size of sericite selvages. This decreasing phyllic alteration and increasing pervasive potassic alteration with depth form an overlapping zone of mixed alteration. Combination of complex vein selvages, i.e., sericite and orthoclase, and the mixed zone of alteration suggest the overprinting of phyllic alteration onto potassic alteration. In the lower portion of the mixed alteration zone and just into the area of intense potassic alteration occurs the zone of significant copper mineralization. There is some suggestion that propylitic alteration may occur below the potassic alteration. Rock from a deep drill hole in the central portion of the American Eagle basin exhibits weak sericite and secondary orthoclase with stronger chlorite-epidote alteration.

Two special alteration minerals, tourmaline and anhydrite, occur at Copper Creek. Tourmaline, schorl variety, is present districtwide and appears to be limited to the upper levels of the deposit. It occurs as acicular crystals in breccias, along veinlets, in quartz-sericite selvages, and as blebs or rosettes in dacite porphyry. Tourmaline may occur alone or may be associated with quartz and pyrite. Purple and white anhydrite is common in the deeper chalcopyrite mineralized zones, occurring as disseminated masses and veinlets.

Mineralization

Significant copper mineralization occurs 2,000 feet or more beneath the surface of the American Eagle basin. It covers an elliptic area approximately 2,500 feet east-west and 1,500 feet north-south. The copper zone underlies a relatively intense east-northeast-trending fracture zone and is associated with a cluster of breccia pipes and dacite porphyry intrusions. Mineralization is hypogene as there is only surficial oxidation and no supergene enrichment. An exception to this is the breccia pipes where oxidization and leaching may occur 100 to 200 feet in depth.

The copper porphyry system at Copper Creek is a relatively low sulfide system in comparison with most Southwest porphyry systems. Dominant sulfides are pyrite and chalcopyrite. Minor amounts of bornite and molybdenite are present in the deeper portion of the system, and galena and sphalerite have been noted in the periphery. Sporadic occurrences of specularite have been noted, especially in some breccias and strongly altered zones. Within the system there is a pronounced vertical zoning of sulfides. Pyrite with very minor chalcopyrite is the principal sulfide in the upper portions of the deposit. With depth, pyrite diminishes and chalcopyrite becomes dominant. Within the copper-rich zone, chalcopyrite is the principal sulfide. At the base of the system, bornite appears and may form up to half of the sulfides. Some high-level chalcopyrite and occasional bornite does occur at Copper Creek and is associated directly with certain breccia pipes.

Surface expression of mineralization at Copper Creek is not overly impressive. Granodiorite and dacite porphyry host limonite-stained breccias and are cut by oxidized quartz-pyrite veins. Visible copper oxides are rare, al-

though geochemically anomalous amounts of copper are found in the veins and breccias.

Sulfide mineralization in the Copper Creek porphyry copper system is controlled primarily by fractures. Other noted mineralization occurrences are disseminated sulfides in quartz-sericite and some porphyries and sulfides as intrafragmental fillings in breccias. In the upper portion of the system, veins are steeply dipping, but with depth nearly horizontal veins become abundant. Rapid decrease in both fracture density and total sulfide content marks the base of the copper-rich zone.

Summary

Copper Creek is the location of past exploration, moderate mine production, and recent discovery of a deep porphyry copper system. Geologic work to date has furnished a preliminary understanding of the igneous activity, hydrothermal alteration patterns, and mineralization within this district. Interpretation of this knowledge forms the basis for the continuing exploration. Copper Creek is important to the understanding of porphyry copper systems because it furnishes a chance to study the upper level occurrence of a deep mineralized porphyry copper deposit.

During Laramide time Precambrian and Paleozoic sedimentary and Mesozoic volcanic rocks of the Copper Creek area were intruded and thermally altered by three granodiorite stocks. The central Copper Creek stock is the site of later dacite porphyry intrusions and related hydrothermal alteration and mineralization. These porphyries occur in and west of the granodiorite stock as plugs and dikes crudely grouped in three northwest-trending zones.

The early pink porphyry appears to be a hydrous potassic and siliceous end member of the granodiorite. There are no known breccias associated and very minor copper mineralization present with this dacite porphyry variety.

Dark porphyry and feldspar porphyry are younger dacite porphyry varieties with which the alteration, mineralization, and breccia pipe development are closely associated. These porphyries occur as plugs, often forming a cluster, and were intruded over a period of time. The location, shape, and clustering patterns of these plugs were influenced by northwest, east-west, and less prominent north-south and northeast structural zones.

The forceful injection of these porphyries into brittle rock caused intense fracturing and brecciation above and adjacent to the plug. This is indicated by the occurrence of intrusion breccias and breccia pipes adjacent to many of the dacite porphyry intrusions. Contemporaneous development of intrusions and brecciation, probably by multiple injections, is shown by the occurrence of porphyry in breccia both as fragments and dikes. Some additional brecciation may be caused by collapse due to volume reduction through magma pressure fluctuations or its crystallization. These zones of fracturing and brecciation became channelways for later hydrothermal solutions. In this manner additional breccia development and textural enhancement occurred by alteration and leaching.

The American Eagle Basin, an area of strong surface alteration and containing a cluster of breccia pipes and dacite porphyry plugs, is where the deep zone of porphyry copper mineralization occurs. In this system the principal alteration and mineralization are fracture controlled. Superimposed on this is the less prominent, but spectacular mineralization controlled by breccia pipes and porphyry plugs. Initial hydrothermal alteration appears to have been potassic. With time and changing hydrothermal fluid composition, the alteration shifted into the phyllic field. This is indicated by the complex vein selvages where potassic alteration often borders the interior sericitic alteration, and the overlapping of serictic alteration onto increasing potassic alteration with depth in the American Eagle basin.

Mineralization in the American Eagle basin exhibits a strong vertical zonal pattern. Pyrite is the dominant sulfide in the upper portions of the porphyry system. With depth chalcopyrite increases to where it is the principal sulfide. Deep within the system bornite occurs. Significant copper mineralization is found in the lower mixed alteration zone and upper potassic alteration zone. Breccia pipes distort this picture somewhat by bringing chalcopyrite and some bornite mineralization high into the system.

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A GEOCHEMICAL STUDY OF THE KALAMAZOO PORPHYRY COPPER DEPOSIT, PINAL COUNTY, ARIZONA

by

Maurice A. Chaffee [1]

Abstract

The region encompassing the southwestern United States and the adjoining sections of northern Mexico contains the highest density of known porphyry copper deposits in the world. It seems likely that most of the exposed porphyry copper deposits that exist in this region have now been found. As a consequence, exploration for new deposits of this type requires the development of techniques or approaches capable of detecting mineralized rock that does not crop out. This search for new approaches has created renewed interest in whole-rock geochemistry. To learn more about the geochemistry of porphyry copper deposits and the potential of rock geochemistry in the exploration for blind porphyry copper deposits, a study was made of a deposit of this type: the Kalamazoo deposit near San Manuel, Pinal County, Arizona.

Three major geologic units are present in the area of the Kalamazoo deposit and the nearby San Manuel deposit. These units include (1) a Precambrian quartz monzonite (Oracle Granite of Peterson) batholith, (2) a Cretaceous monzonite porphyry stock that intruded the batholith, and (3) Cretaceous and Tertiary conglomerates and sedimentary breccias and intercalated volcanic rocks. The Kalamazoo and San Manuel deposits are offset, rotated segments of a single mineral deposit genetically and spatially associated with the Cretaceous stock. The deposits occur both in the Precambrian quartz monzonite and in the Cretaceous monzonite porphyry.

Samples of cores and cuttings from four holes drilled through the Kalamazoo deposit were analyzed for bulk density and for as many as 62 different elements. Two of the holes penetrated both the alteration zones (propylitic to potassic) and the ore zone (+0.5% Cu) near the top of the deposit as it existed before tilting. The other two holes intersected the ore zone near its roots.

The distributions of values for bulk density were compared to the distributions of concentrations for most of the elements. The variations in bulk density correlate directly and most closely (and at a highly significant level) with variations in concentrations of sulfur and iron. These correlations suggest that the density values are basically a measure of the pyrite content of the samples.

Of the 62 elements determined, at least 20 show distinct zones of high or low concentrations that are spatially related to the alteration zones, the pyrite zone, and the copper ore zone. Minor or trace elements provide more useful information than do most of the major rock-forming elements.

Some of the elements determined in this study, or the ratios of certain elements, may be useful in identifying the zoning of specific minerals or mineral groups; for example, the ratio of Fe/Mn (and possibly the ratios of Fe/Mg and Fe/Ca) can be used to separate those iron anomalies related to pyrite in the pyrite zone from those related to other minerals. The spatial distribution of other elements or other element ratios may be useful for defining zones containing high concentrations of less obvious minerals that are more difficult to identify in either hand specimens or in thin sections than is pyrite.

Examination of depth—versus—concentration curves for the 20 selected elements indicates that the curves for these elements can be classified into one or more of four types. Elements forming Type 1 curves (B, Ba, Sr, Li) have their highest concentrations in the lower half of the ore zone or below the ore zone in the barren or low-grade core of the de-

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posit. Type 2 curves include those elements (Cu, Mo, Ag, Au, Te, K) concentrated in the copper ore zone. Type 3 curves include those elements (Co, V, Se, Fe, S, Rb, Au, Te) that have positive anomalies in aureoles outside the ore zone. Type 4 curves include those elements (Mn, Zn, Pb, Tl) that seem to form negative anomalies relative to the ore zone. It is probable that Type 4 curves are really Type 3 curves having positive anomalies in aureoles well beyond those of the Type 3 elements.

A study of the locations of intervals of high element concentration and of the locations of coincidences of element concentration peaks suggests that a three-dimensional geochemical model of the Kalamazoo deposit can be synthesized. The elements forming Type 2 curves probably are concentrated in a roughly cylindrical zone surrounding the core zone. The elements forming Type 3 curves seem to occur in four different aureoles that surround the ore zone at varying distances. With increasing distance from the ore zone, the elements in these four aureoles are (1) Co, V, and Se; (2) Fe and S; (3) Rb; and (4) Au and Te. The first three of these aureoles seem to occur concentric to the ore-zone aureole. There are two separate zones in which the concentrations of both Au and Te are high; the inner zone coincides with the cylindrical ore zone, whereas the outer one seems to be conical in form, expanding rapidly outward with depth. The elements forming Type 4 curves probably occur in the outermost aureoles.

Geochemical exploration programs using whole-rock samples must take into account the effects of chemical weathering. Of the 20 elements selected for this study, Cu, Zn, and Rb were the only ones that were not generally depleted by weathering processes. Less complete information suggests that Au, Ag, Pb, Te, and Se were also relatively unaffected by weathering.

At Kalamazoo, the concentrations and spatial positions of a suite of ore-related elements could have been used to locate this blind deposit. If other porphyry copper deposits with similar alteration-mineralization zoning also exhibit chemical zoning similar to that found at Kalamazoo, then multielement zoning should be useful in the search for other blind deposits contained within exposed rock bodies.

GEOLOGY AND MINERALIZATION OF THE RAY SILICATE OREBODY, PINAL COUNTY, ARIZONA

by

Neil A. Gambell

Abstract

The Ray orebody is owned and operated by Kennecott Copper Corporation and is located in eastern Pinal County, Arizona, 85 miles southeast of Phoenix. The orebody has been a major copper source since 1911, producing an estimated 2.2 million tons of copper. The bulk of this production has been derived from sulfide ores.

The Ray deposit is a porphyry copper with ore grade (0.4%+ Cu) hypogene and supergene sulfide mineralization largely restricted to Precambrian host rocks consisting of schist, quartzose sedimentary rocks, and diabase intrusive rocks.

Associated with the sulfide deposit is a complex body of silicate copper mineralization. By the early 1960's, drilling had delineated some 93 million tons of potential ore and a program of research and pilot plant studies was initiated to develop a viable extraction process. Success was realized in 1969 when a vat leaching system utilizing sulfuric acid from the smelter acid plant began production.

Silicate copper mineralization is found in the Precambrian Pinal Schist, Pioneer Formation, Dripping Spring Quartzite, diabase, and to a lesser extent in the early Tertiary Granite Mountain Porphyry. In postmineral rocks, significant amounts of silicate copper are present in the Whitetail Conglomerate and the Apache Leap Tuff.

The distribution of the silicate copper mineralization suggests that it developed in the core zone (low total sulfide, high chalcopyrite) of the sulfide system. Erosion, faulting, and folding also played an important role in localizing the orebody. Although the work is still in progress, the deposit appears to show definite zoning patterns in secondary mineral assemblages, and it is possible to demonstrate some paragenetic relationships.

Geologic aspects that affect the amount of copper recovered by the leaching process are the ore mineralogy, gangue mineralogy, rock type, and the nature of the mineralization (vein-fracture or disseminated).

In an attempt to anticipate potential problem areas, the construction of contour maps for feet percent copper and percent readily soluble of the total copper for the major lithologic types is a useful tool.

The term "silicate" is used in referring to the orebody because of the abundance of chrysocolla; however, the deposit also contains copper-bearing manganese wad, copper montmorillonite and halloysite clays, copper-iron oxide complexes, malachite, cuprite, libethenite, dioptase, azurite, native copper, and chalcocite.

At the present time, 10,000 tons of silicate ore are being mined on a five-day basis. This ore is crushed to minus 1/2 inch, classified (coarse fraction to leach vats; slime fraction to a thickener circuit), and leached with a 35 g/l sulfuric acid solution. After a ten-day leach cycle, a pregnant solution containing 20-35 g/l copper is sent to electrowinning. To date recoveries have ranged from 45 to 75 percent of the total copper with an acid consumption of approximately 100 pounds per ton of ore treated. Early in 1976, a 4000-ton-per-day expansion of silicate ore will be initiated with the completion of a new grinding and agitation leaching circuit. This circuit will allow utilization of increased acid production brought about by environmental considerations and yield better classification of the ore. At current operating rates, the silicate plant will produce some 28,000 tons of copper per year.

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VEKOL HILLS COPPER DEPOSIT, PINAL COUNTY, ARIZONA

by

H. J. Steele [1]

Abstract

The Vekol Hills copper deposit is located on the Papago Indian Reservation, Pinal County, Arizona, about 25 airline miles southwest of Casa Grande on the easterly sloping pediment at the northeast edge of the Vekol Mountains.

The stratigraphic succession of formations in the vicinity of the deposit consists of the Precambrian Pinal Schist and related granitic intrusive rocks unconformably overlain by the upper Precambrian Apache Group of sedimentary rocks and intrusive diabase. This sequence in turn is unconformably overlain by the Cambrian Bolsa Quartzite and Abrigo calcareous siltstones and shales. The Devonian Martin and Mississippian Escabrosa Limestone are present in sequential order followed by Mesozoic quartzites and conglomerates of the Phonodoree and Vekol formations. Stocks, dikes, and sills of Laramide(?) quartz, feldspar, and hornblende porphyries intrude all the aforementioned rocks. The sedimentary rocks strike northeasterly and dip 30°-40° NW.

Mineralization at the Vekol Hills deposit occurs in diabase sills, quartzite, limestone, shale, and sandstone of Precambrian to Devonian age. Minor mineralization is found in the Laramide(?) porphyry. Primary mineralization occurs as pyrite, chalcopyrite, and molybdenite as fracture fillings and disseminations throughout the host rock. Oxidation and supergene enrichment is relatively unimportant in the total volume of mineralized material in the deposit and its distribution is dependent in part on lithology and major fracture controls.

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INDUCED-POLARIZATION DEPTH PENETRATION IN EXPLORING FOR PORPHYRY COPPERS

by

C. L. Elliot[1] and H. David MacLean[2]

Abstract

The induced-polarization response of a mineralized system measured at surface is a function of several factors: (1) the spacing of the electrode configuration, (2) the physical dimensions of the mineralized system, (3) the intrinsic response of the system, and (4) the resistivity distribution of overlying or surrounding materials. These factors may be ideally summarized in the response expression

$$R = \Sigma B_j \Delta_j$$

where Δ_j is the physical property contrast and B_j is a weighting coefficient which is primarily dependent on the geometry of the responsive zone and the sensor. The physical property contrast associated with porphyry copper systems is generally small, but in the case of shallow systems, the above equation can be completely dominated by an appropriate electrode spacing that keeps the weighting coefficient associated with the porphyry copper system large in relation to that associated with the surrounding less responsive material. However, if target depths increase, this relationship is maintained only with increasingly greater difficulty.

The resolution of the resistivity distribution of overlying strata is essential to the analysis of the depth penetration of a given IP survey system, and a knowledge of the shallow or near-surface layers becomes increasingly important as the resistivity section becomes more complex. Thus, no matter how great the anticipated depth of a target zone, closely spaced electrode configurations are essential so that the resistivity section can be analyzed and a suitable array for the expected exploration depth can be devised. Under certain adverse conditions where the electrode spacings are limited by electrical noise or target size considerations, the resistivity relationship of the target and overlying media might limit the search depth of conventional IP exploration systems to unacceptably shallow depths.

The depth of penetration of IP systems where the electrode spacing is limited is almost entirely a function of resistivity, and this factor must be critically analyzed before an estimate of search depth can be made. By a careful choice of IP electrode arrays and survey procedures based on measurements from an orientation survey, detection of mineralized systems at depths of 1,500 to 2,000 feet is possible with conventional systems. No doubt detection at even greater depths will be possible under favorable resistivity conditions and as more effective electrical noise suppression techniques become available.

Introduction

The induced-polarization method has found general acceptance in the Southwest and is widely used and regarded for porphyry copper exploration in areas where the thickness of cover is of the order of 300 to 400 feet or less. Recently, interest in exploration to much greater depths has developed; target zones are frequently below 1,000 feet or even as much as 2,500 feet of cover. In order to assess the induced-polarization response from targets at such depths, it might be instructive to compare the theoretical induced-polarization response that can be expected from these deeper targets with that from the shallower features with which we are all familiar. The factors that influence induced-polarization depth penetration are listed below. The relative importance of these factors as target depths increase varies and factors of almost trivial

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consequence when exploring for shallow features tend to dominate the surface response if the target is located at a considerable depth.

Any geophysical response measured at the surface from any source is affected or controlled by the following factors:

1. The intrinsic response of the system.
2. The sensor configuration used and the spacing of the sensors.
3. The physical dimensions of the mineralized system.
4. The resistivity distribution of overlying and surrounding material.
5. Noise. Under some circumstances, noise is the dominant observed phenomenon.

The geophysical response, R, from a particular target medium such as that shown in Figure 1 can be stated by the expression

$$R = \Sigma B_j \Delta_j + \text{noise}.$$

where Δ_j is the physical property contrast or intrinsic response of a particular rock unit and B_j is the corresponding weighting coefficient for that same unit. The response R is the sum of the products of the intrinsic response and an associated weighting coefficient for all of the media that affect the geophysical sensor. Generally, this weighting coefficient shown in the equation above is primarily dependent on the geometry of the responsive zone and the point of measurement.

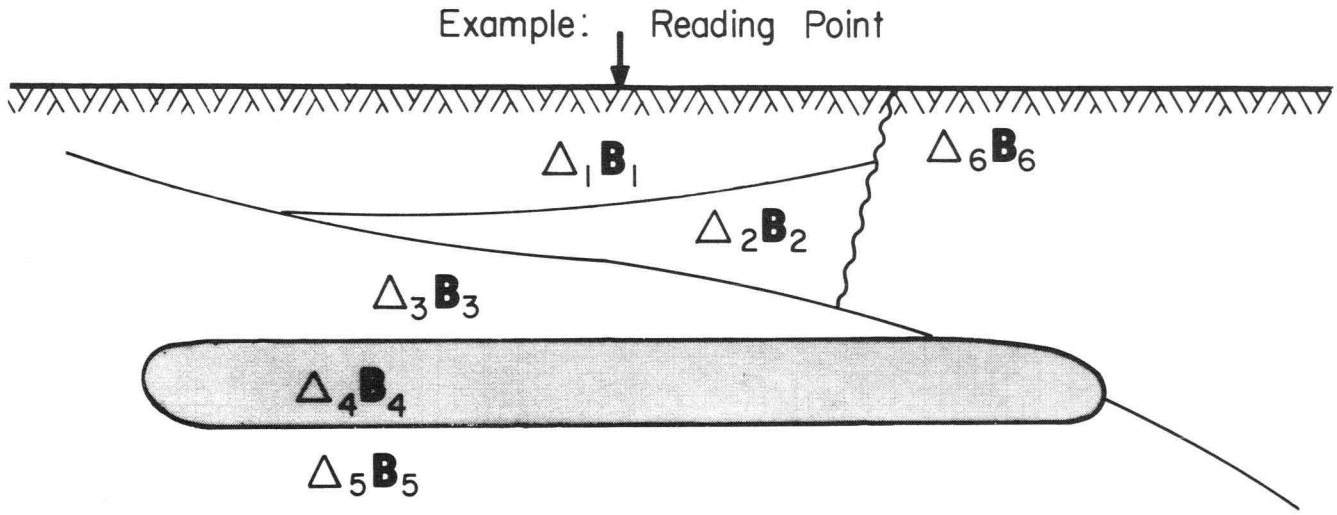
The induced-polarization response differs from the general case, however, in that the weighting factors are dominated primarily by resistivity rather than by geometry as will be demonstrated later in this paper. The IP response at surface from a particular target zone surrounded by other less responsive media such as in the case shown in Figure 1 can be stated just as the general case. The apparent IP response of unit 4, which is the target zone, will be modified by weighting coefficient B4; if this coefficient is large compared to all of the other coefficients and if the intrinsic response or chargeability of the target zone is large compared to the response of all other media, the target zone can be easily observed at surface. If, however, the weighting coefficient B4 is small and the physical property or chargeability contrast of the unit is not appreciable, the anomalous IP response measured at surface would be small and may even be included within the noise envelope for a particular observation site; if this is the case for all survey observation points, the unit will be undetectable by the IP method.

The physical property contrast measured by IP systems, which is variously called chargeability or frequency effect or phase angle (the terms are all mathematically interrelated), is relatively small. Under the best of circumstances, the chargeability of a mineralized body is only 9 to 10 times that of the enclosing media, and it is frequently only 3 to 5 times greater than the intrinsic background level. The IP response of some rock types and overburden material are listed in Table 1 and the intrinsic IP effects associated with some mineralized systems are presented in Table 2. These tables have been summarized from Brant (1966) with some additions of more recently studied areas. Note that the IP response of the mineralized areas is only 3 to 5 times that of the background level associated with many rock types and only in exceptional cases is the IP response as much as 10 times background.

Table 1. Examples of IP response and resistivity encountered in some characteristic southwestern rock types

Rock Type	Resistivity (ohm-meter)	Chargeability ms	PFE
Alluvium	20-100	1-14	≈ 0.5
Gila Conglomerate	30-300	4-15	≈ 2
Tertiary volcanics	20-1000	3-17	1-4
Precambrian volcanics	200-5000	8-20	1-4
Granite, monzonite, diorite	100-1000	6-15	1-2
Precambrian gneiss and schist	50-5000	6-30	1-4
Sandstone	40-1000	3-12	0.5-2.0
Limestone and dolomite	200-10,000	5-15	1-2
Quartzite	100-5000	5-12	≈ 1-2

IP survey systems designed to detect relatively shallow deposits of large extent and at least moderate chargeability contrast can easily be arranged so that the response equation shown above can be dominated by the weighting coefficients B_j. If the IP configuration or electrode spacing can simply be made very



$$R = B_1\Delta_1 + B_2\Delta_2 + B_3\Delta_3 + B_4\Delta_4 + B_5\Delta_5 + B_6\Delta_6 + \text{Noise}$$

Fig. 1. Factors affecting the geophysical response at surface from a target zone surrounded by other material. For the IP response, Δ depends on the IP contrast of the units and B depends on the array geometry, system geometry, and resistivity.

Table 2. Examples of resistivities and IP response encountered in some southwestern porphyry copper deposits

Mineralized Area	Resistivity (ohm-meter)	Chargeability ms	PFE
San Manuel 6% sulfide	<100	75	10
Mission 5% sulfide	<100	80-90	12
Cactus 3-5% sulfide	≈ 100	45	3
Castle Dome 4-5% sulfide	≈ 100	60-70	8-9
San Juan, Safford 5-8% sulfide	4-40	50-150	4-15
Quellaveco, Peru 3-4% sulfide	≈ 100	70-80	10
Vekol 5-6% sulfide	≈ 80	60-70	7-8
Florence 1-2% sulfide	30-40	30-40	3-4
Interconnected and massive sulfides in situ	.01-1	10-30	2-5

large relative to the depth of burial, it is intuitively apparent and can be mathematically demonstrated that the weighting coefficient associated with the overburden and enclosing rocks will be small, and the coefficients associated with the mineralization will be relatively large.

A survey system for just such a target is shown in Figure 2, which is a schematic diagram of the dipole-dipole survey array probing for a well-altered and mineralized zone covered by overburden of variable thickness. Implied in the diagram are the conditions that the size of the target zone is much larger than the IP electrode spacing and that the body is substantially thicker than its depth of burial. This hypothetical mineralized zone might approximate the pyrite halo that surrounds many southwestern porphyry copper deposits where pyrite mineralization might run to 5 or 6 percent; the intrinsic IP response would be as high as 70 milliseconds, or 10% frequency effect so that the response of the body is 10 times background.

The IP response measured at surface of the body (shown in Fig. 2), obtained by commonly used IP survey configurations, can be calculated using algorithms developed by the coauthor of this paper, Elliot, and M. Nabighian of Newmont Exploration (Elliot, 1974). From these operators, the IP effect or chargeability measured at surface using the dipole-dipole array and a spacing of 1,000 feet, for the body shown in Figure 2, buried at 300, 1,000,

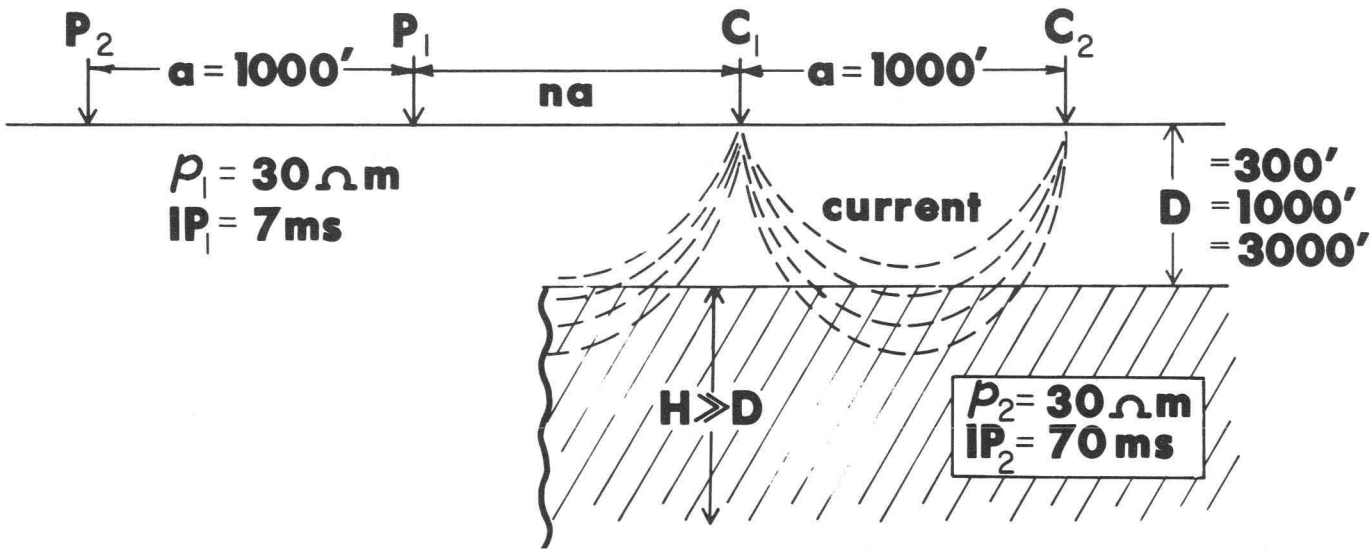


Fig. 2. Schematic diagram showing the dipole-dipole IP survey array and current lines penetrating a buried target zone. The IP response measured at surface for any reading point is $IP_a = B_1IP_1 + B_2IP_2$.

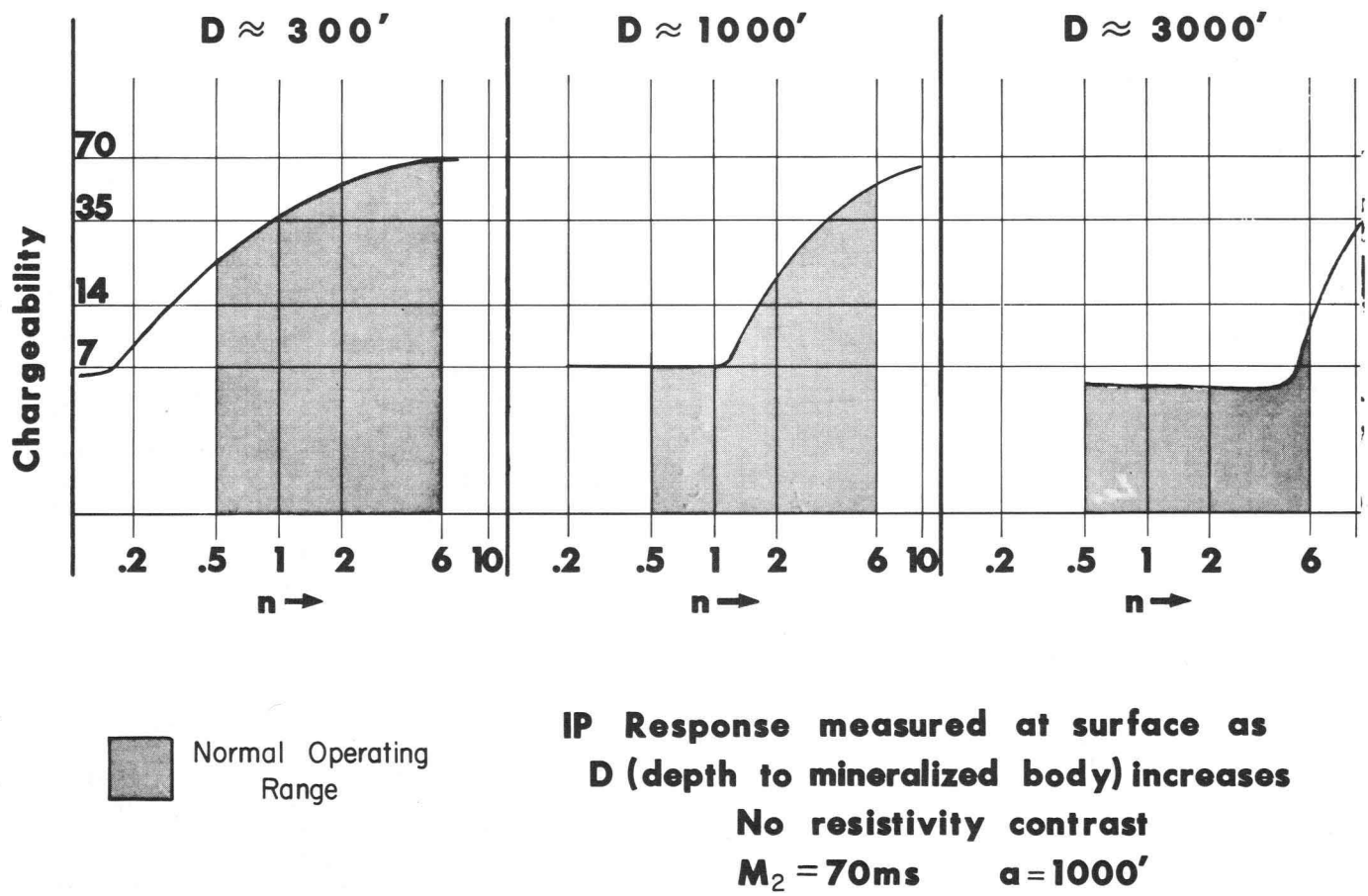


Fig. 3. IP response from the model shown in Figure 2 at depths of 300, 1,000, and 3,000 feet

and 3,000 feet has been calculated and is presented in Figure 3. In these cases there are no resistivity contrasts between the overburden and the target body and the apparent IP at surface is controlled by the intrinsic response and target-sensor geometry only. At a depth of 300 feet, the observed chargeability for n greater than about 2 is almost the same as the intrinsic or theoretical chargeability. Even at an n value of 1, the apparent IP effect is about 36 milliseconds (5 x background) and detection of the body at this depth by the IP method is almost trivial. As the depth to the body increases, the response falls off for any given n value. At a depth of 1,000 feet, an anomalous response is limited to the larger n values, and at 3,000 feet the body is just barely detectable. Within the normal operating range of survey systems, for an electrode spacing of the order of the depth of burial, a strongly anomalous IP effect is obtained from large bodies throughout most of the operating range, perhaps suggesting the popular rule of thumb that the "search depth" of a particular IP survey system should be approximately equal to the electrode spacing. Unfortunately, the interpretation of field cases is not this simple since response factor 4 in the above list, namely the resistivity contrast, has been ignored, and factor 3, the physical dimensions of the system, is assumed to be always much larger than the electrode spacing.

The IP effect at surface of a responsive body falls off appreciably if the size conditions implicit in Figure 2 are not met. Rather than the infinitely large body considered in Figure 2, the target might be a pluglike body, which is approximately 2,000 feet across and buried at depths of 2,000 or 4,000 feet as shown in Figure 4; the intrinsic response of the tabular body is 10 times that of the surrounding media. The IP response measured at surface for this body, using dipole spacings equal to the depth of burial, has been calculated, and is shown in Figure 5. A recognizable anomaly is apparent for the case where the depth of burial is 2,000 feet, but the anomaly almost disappears when the target depth increases to a little over 4,000 feet. Assuming that a survey incorporating a 4,000-foot dipole spacing could be practically executed, the measured anomaly is now barely twice the background and its chances of being detected and recognized under any practical field conditions, where significant amounts of noise will be included in the apparent IP measurement, becomes very much reduced. Further, if the chargeability contrast between the target and enclosing rocks is less than the 10 to 1 shown, the measured anomaly would be even smaller. By using sophisticated electronic circuitry and specialized survey techniques, noise from electrical sources over such dipole lengths can be held low enough so that usable data could be obtained, but noise from geological sources cannot be suppressed inasmuch as it is represented by a true IP signal.

The limitation on depth imposed by the size of the body as illustrated in Figures 4 and 5 is not significant if the IP method is applied to exploration for southwestern porphyry copper systems at shallow depths of 300 to 400 feet. Lowell and Guilbert (1974) describe the "typical" porphyry copper as presenting an oval subcrop pattern having dimensions of 3,000 x 6,000 feet. Frequently the associated pyritic halo is of even larger dimensions. In this case the entire IP survey array of potential and current electrodes can be spread out four or more times the depth of burial and not violate the condition that the target body be large relative to the electrode spacing. Nevertheless, the responses shown in Figure 5 from the models in Figure 4 do suggest an ultimate exploration depth limit imposed by the target size.

Survey conditions encountered in the field produce much less reliable data than the ideal models presented in these figures. Under field conditions physical property contrasts and layer thicknesses are not uniform and the resistivity contrast between the target zone and surrounding materials is usually quite significant. Articles by Rogers (1966) and Maillot and Sumner (1966) point out that porphyry copper systems can be either more resistive or less resistive than the overburden and host rocks. Where porphyry copper systems are shattered and porous, the resistivity will be relatively low; if on the other hand the fractures have been filled with silica, the resistivity of this same basic system will be much higher. Tables 1 and 2 show the resistivity range of some porphyry copper systems and of some typical host rocks. The flow lines of the charging or inducing electrical current from an induced-polarization survey system will tend to concentrate in the lower resistivity material. A distortion of the current flow lines under these contrasting resistivity conditions is shown schematically in Figures 6 and 7. If the overburden or enclosing rocks are less resistive than the target, as illustrated in Figure 6, a greater amount of the current will flow within the enclosing rocks and will avoid the target. Similarly, if the target consists of a low-resistivity material, as in Figure 7, the current flow will be trapped and cannot escape to affect the measuring electrodes.

The response that could be expected from the body illustrated in Figures 6 and 7 for burial depths of 300, 1,000, and 3,000 feet using a dipole-dipole electrode array with a

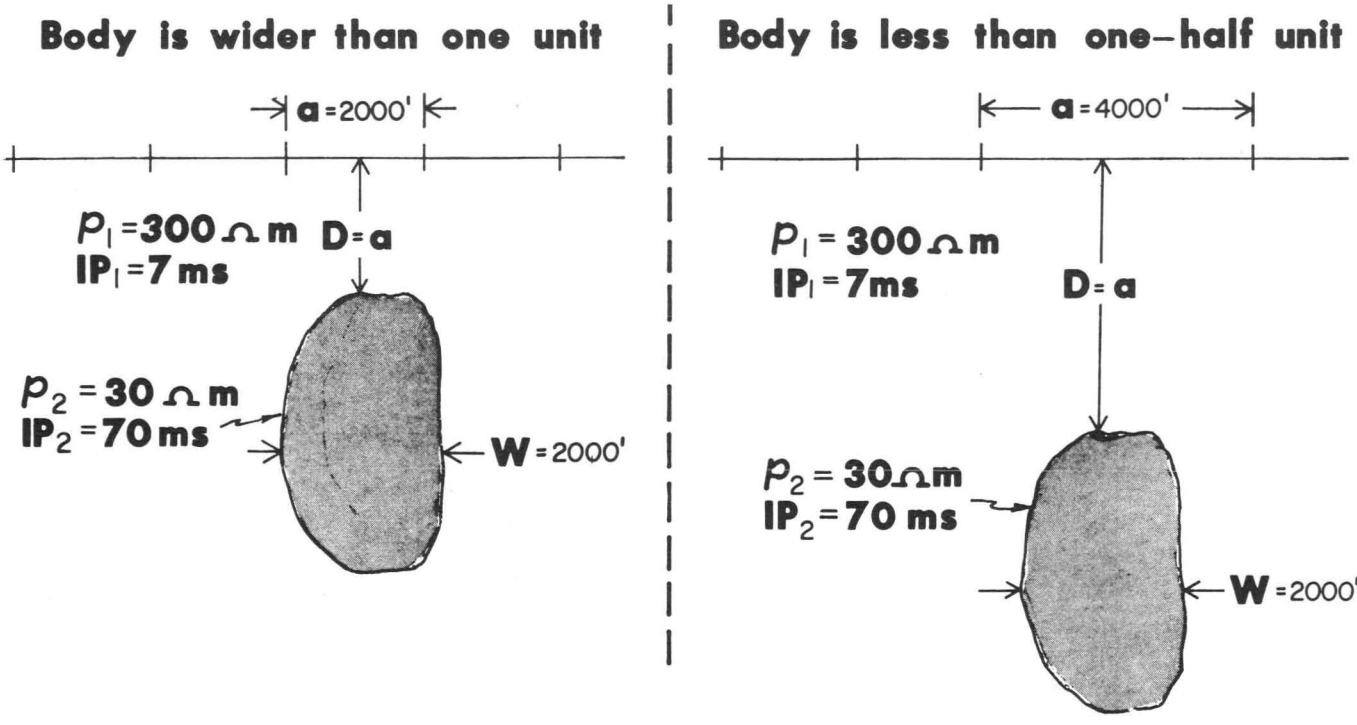


Fig. 4. Model porphyry copper target buried at 2,000 and 4,000 feet

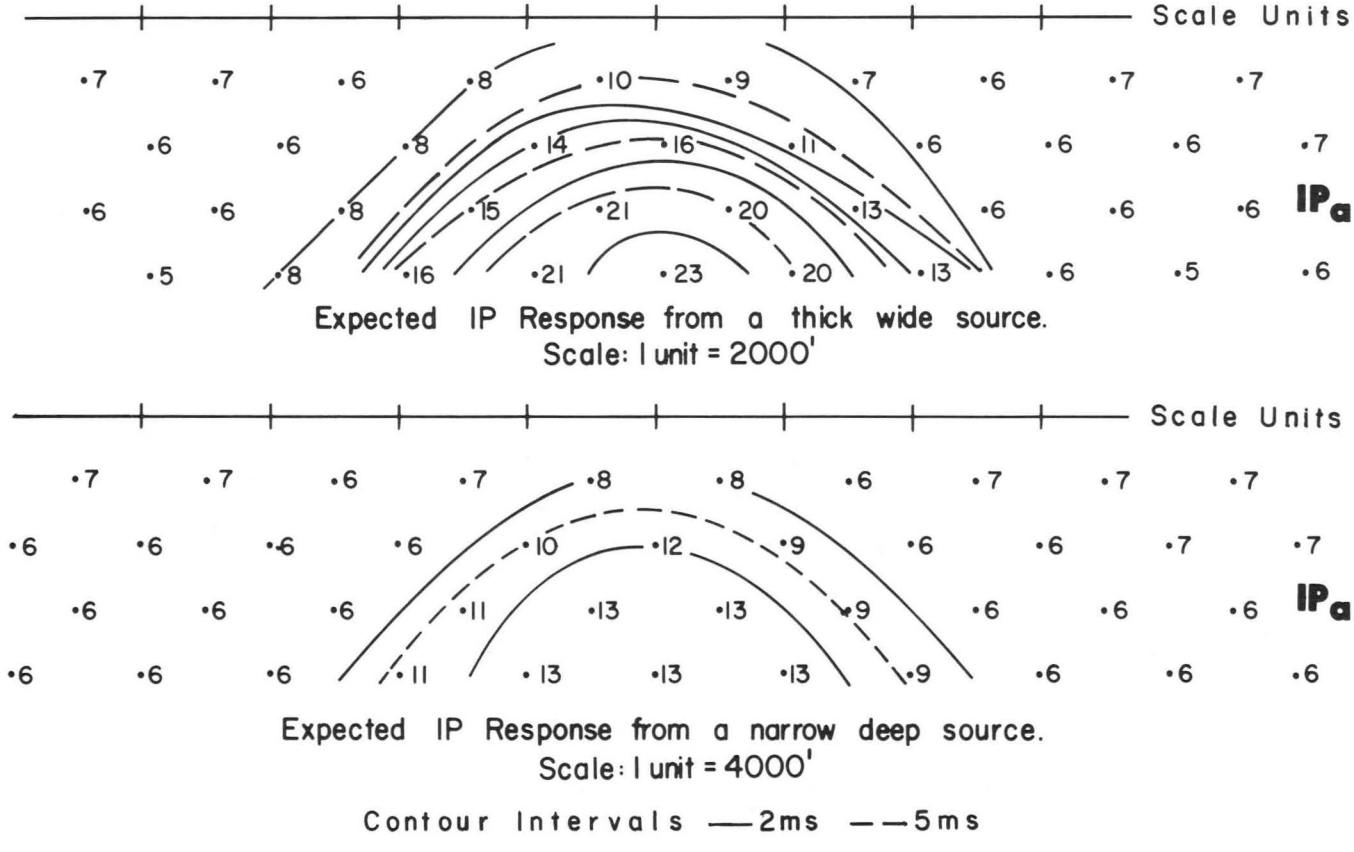


Fig. 5. Expected IP response from source shown in Figure 4; response at depth 2,000 feet above and 4,000 feet below. No electrical, cultural, or geologic noise assumed.

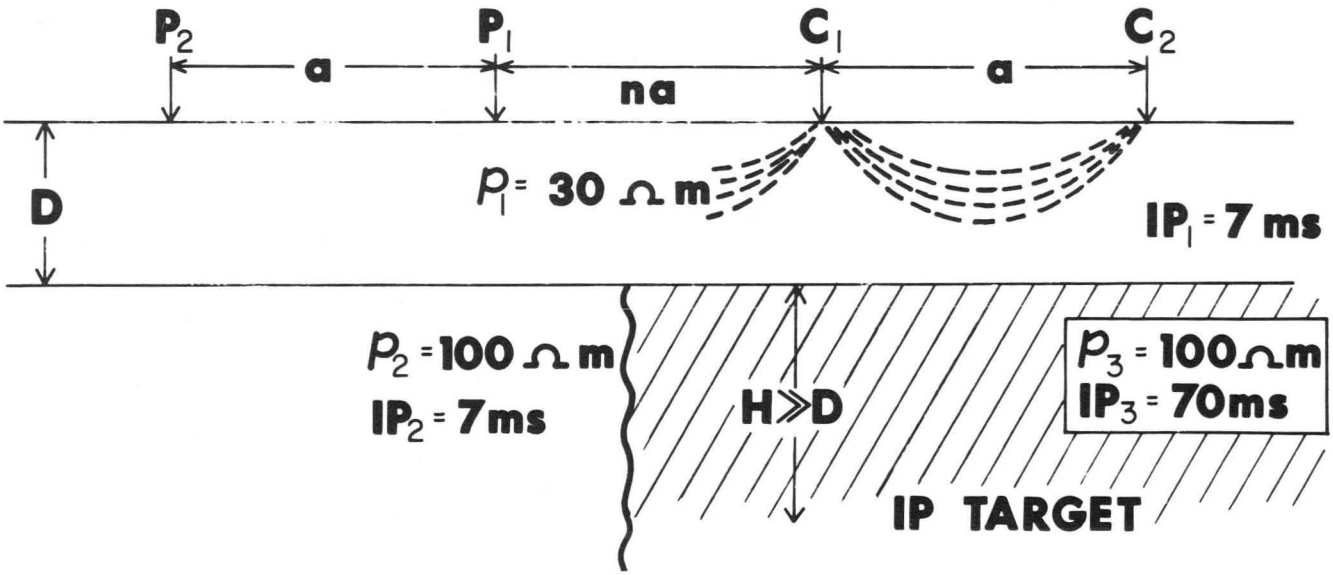


Fig. 6. Schematic diagram showing distortion of current lines from IP survey electrodes if source is more resistive than overlying material. The IP response is $IP_a = B_1IP_1 + B_2IP_2 + B_3IP_3$.

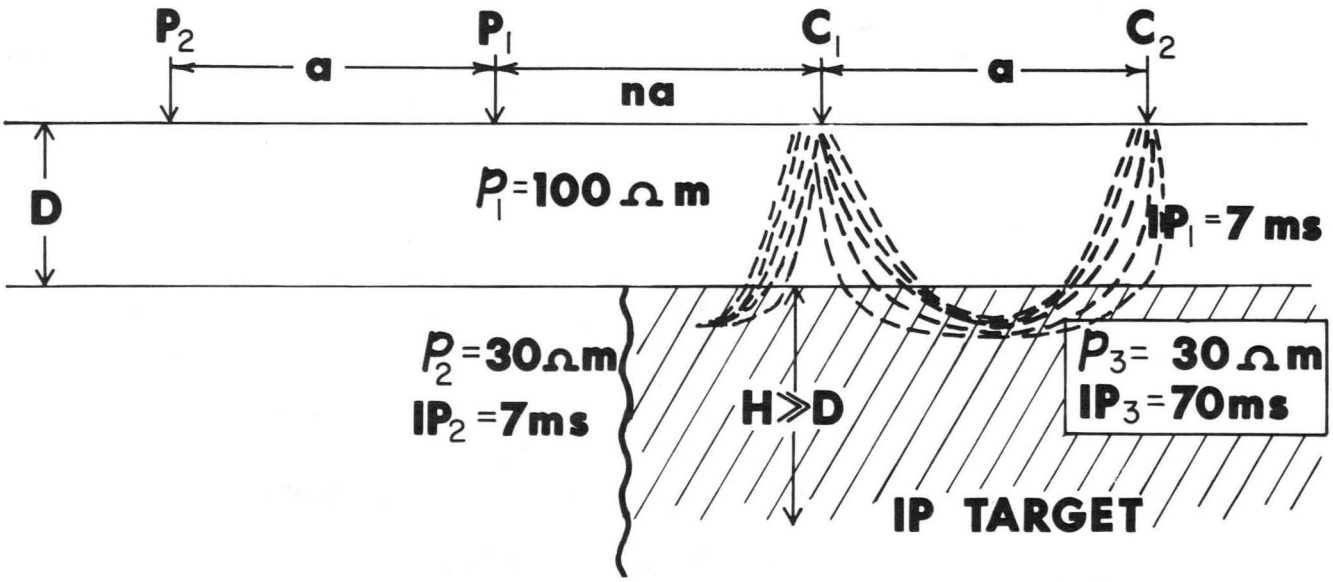


Fig. 7. Schematic diagram showing distortion of current flow from IP survey electrodes if IP target is less resistive than overlying rocks. The IP response is $IP_a = B_1IP_1 + B_2IP_2 + B_3IP_3$.

spacing of 1,000 feet is shown in Figure 8. The solid curve represents the optimum no-resistivity contrast and is simply a repeat of the response shown earlier. The dashed curve indicates the response that could be expected if the overburden resistivity is 1/3 the resistivity of the target material. The dotted curve illustrates the response that could be expected if the overburden resistivity is greater than that of the target zone. In both cases of resistivity contrast, no matter whether the overburden is more or less resistive than the target, the IP response at surface is reduced from the optimum obtained with no resistivity contrast, and if the resistivity of the cover is lower than that of the mineralized target zone, the body is just barely detectable within the envelope of information normally supplied if the a spacing is of the order of the depth of burial. Chances of recognizing a body under these conditions at a depth of 1,000 feet would be improved if the electrode spacing were increased to something like three times the expected depth of burial, but the noise level and logistics problems that would be encountered with 3,000-foot-long dipoles might make the survey unfeasible.

Even the simple resistivity contrast situation shown here is relatively ideal. The material covering porphyry copper systems, particularly those at depth, frequently consists of two or more components of different resistivity. The overburden might consist of dry and wet gravels, or the cover can be unmineralized rock, which is in turn overlain by sand, gravel, or clay. A realistic, if not typical, porphyry copper exploration case is shown in Figure 9 where the total overburden thickness approaches 1,000 feet. Here a high-resistivity silica mineralized zone, which is 10 times more responsive than the enclosing rocks, is covered by 700 feet of lower resistivity volcanics and an additional 300 feet of low-resistivity gravel. A pseudosection showing the apparent chargeability measured at surface for the dipole-dipole array using 1000-foot spacing (the depth of burial of the body) is shown in Figure 10. Within the normal operating range, the body is just barely detectable

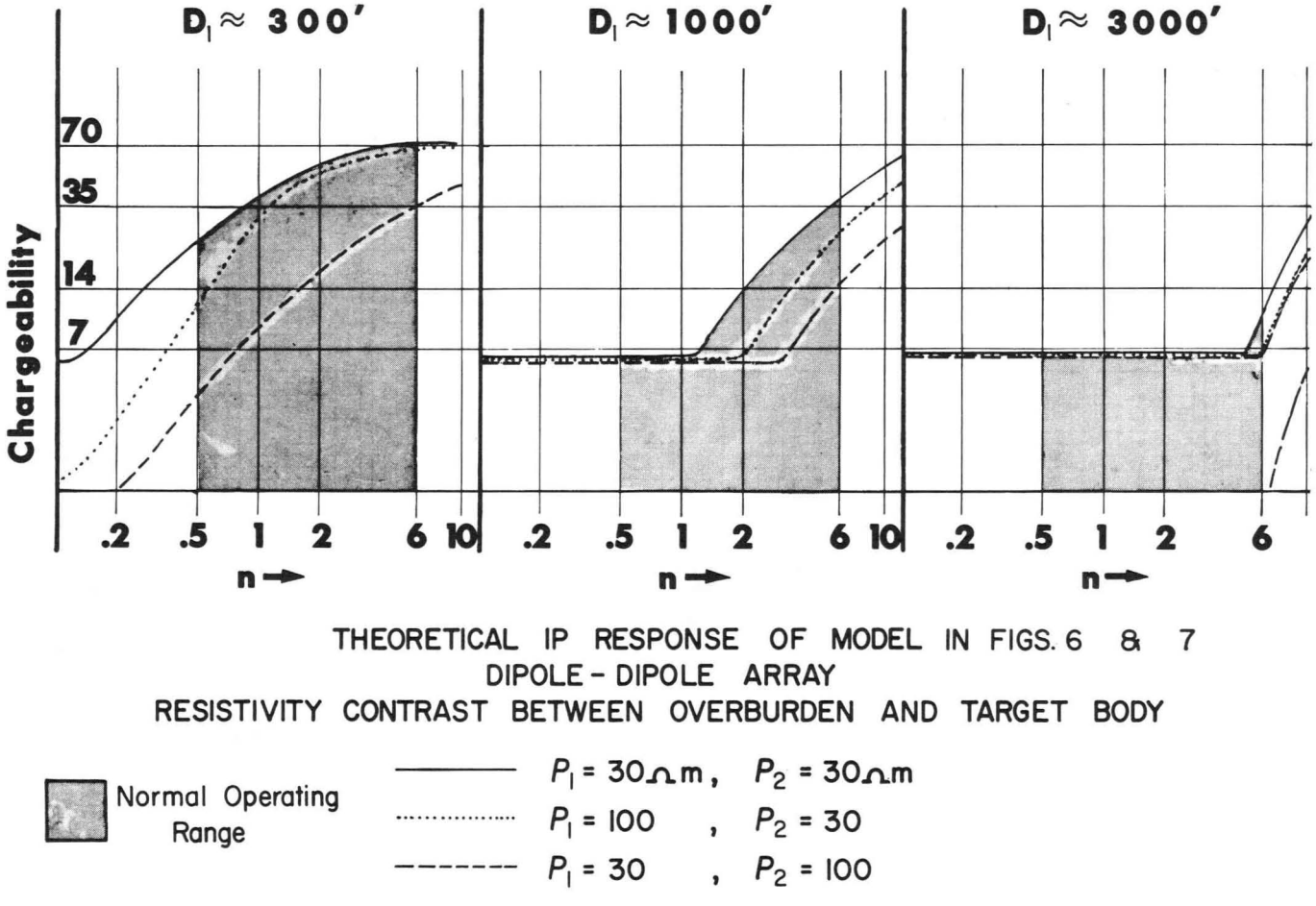


Fig. 8. IP response from model shown in Figures 6 and 7

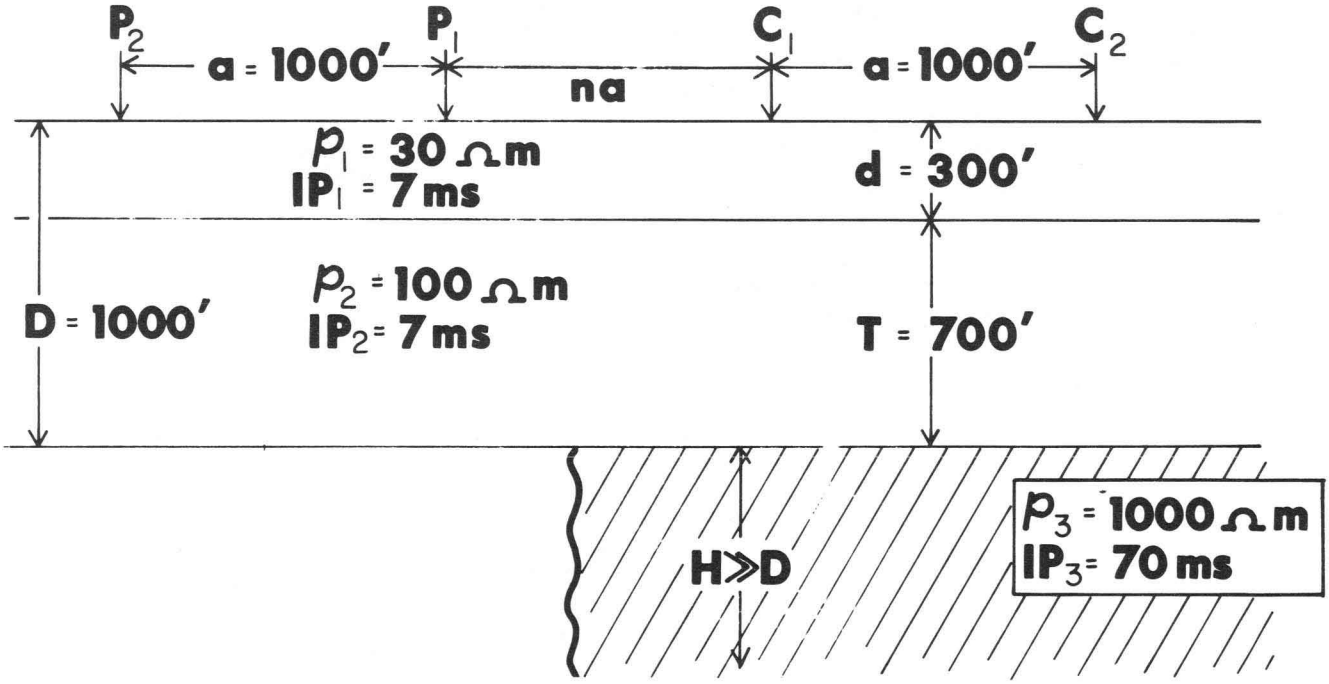


Fig. 9. Three-layer IP target model. High-resistivity target (4% highly silicified sulfide body) overlain by two resistive overburden layers.

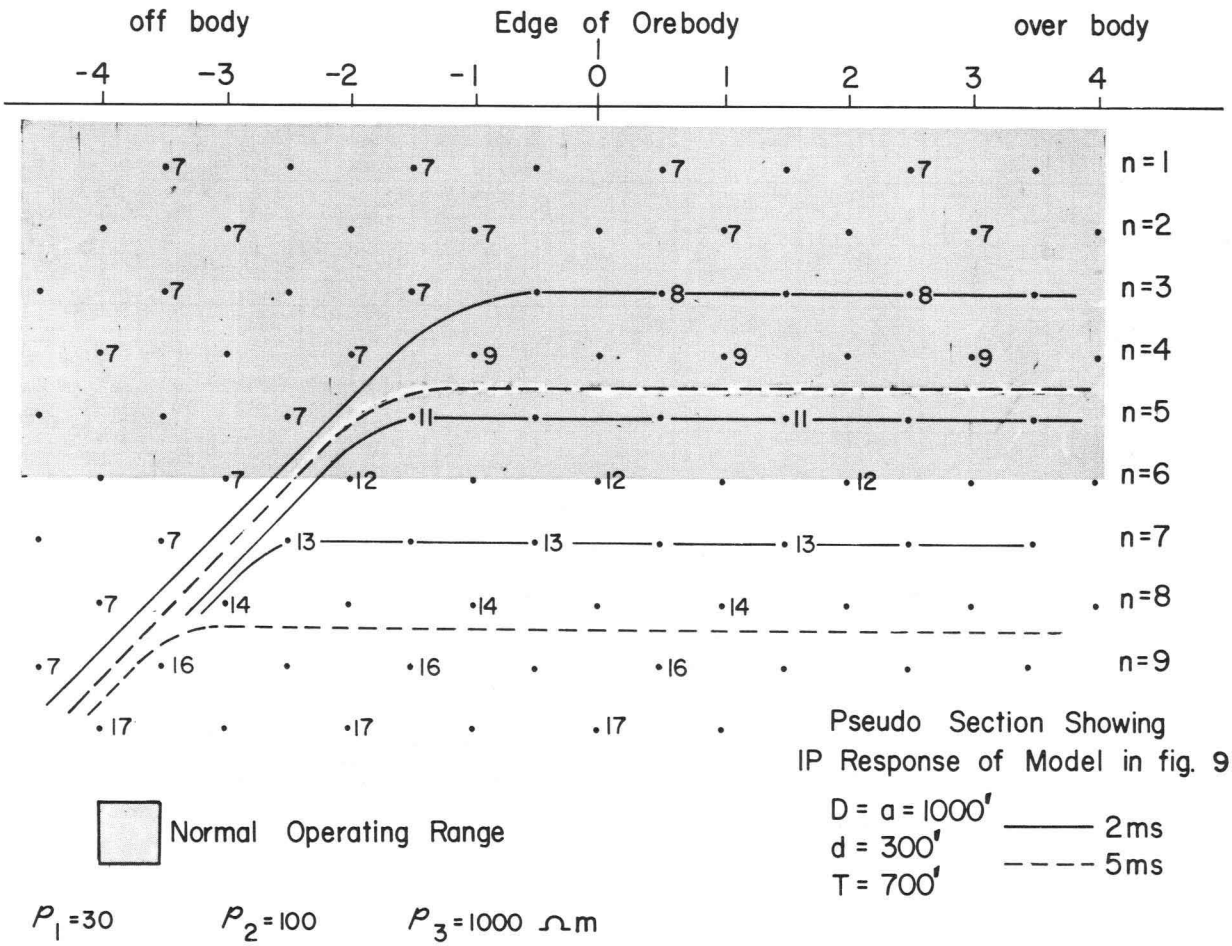


Fig. 10. IP response from model shown in Figure 9

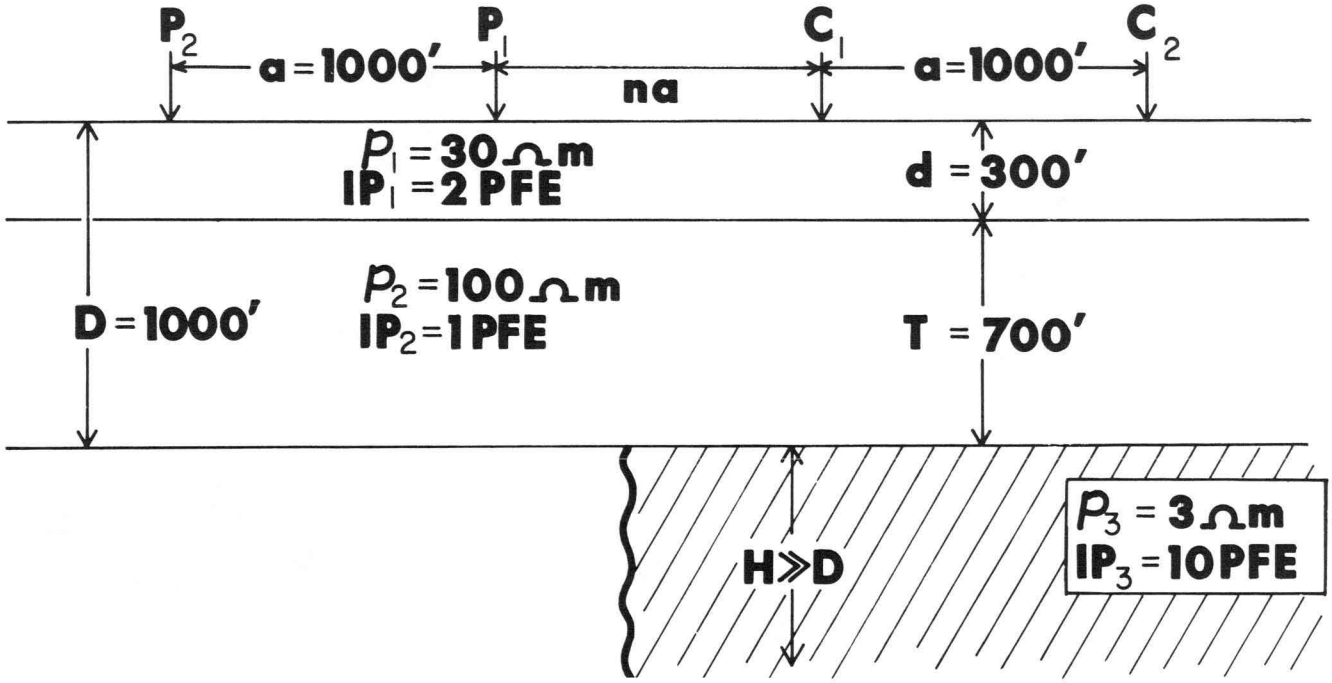


Fig. 11. Three-layer IP target model. Low-resistivity target (4% highly fractured sulfide body) overlain by two-layer resistive overburden.

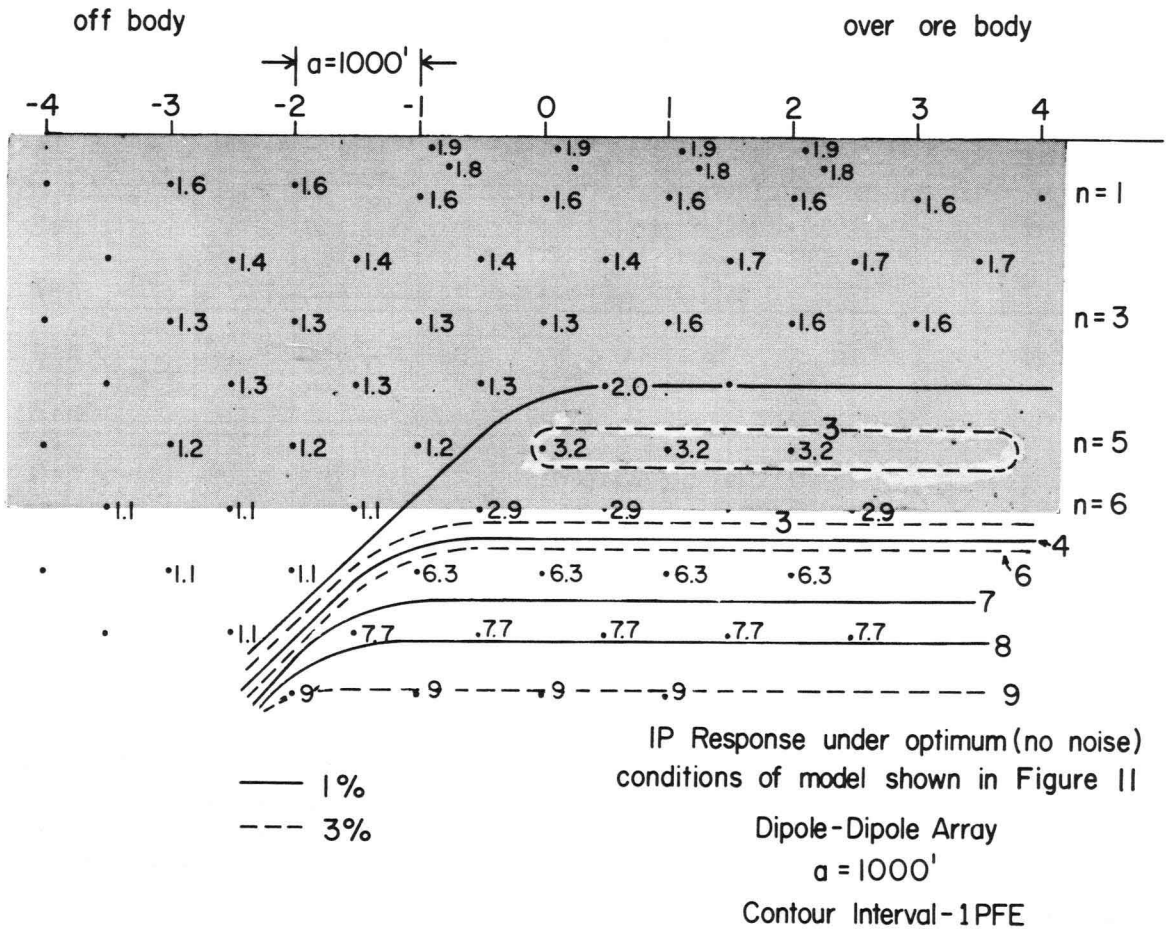


Fig. 12. IP response from target shown in Figure 11

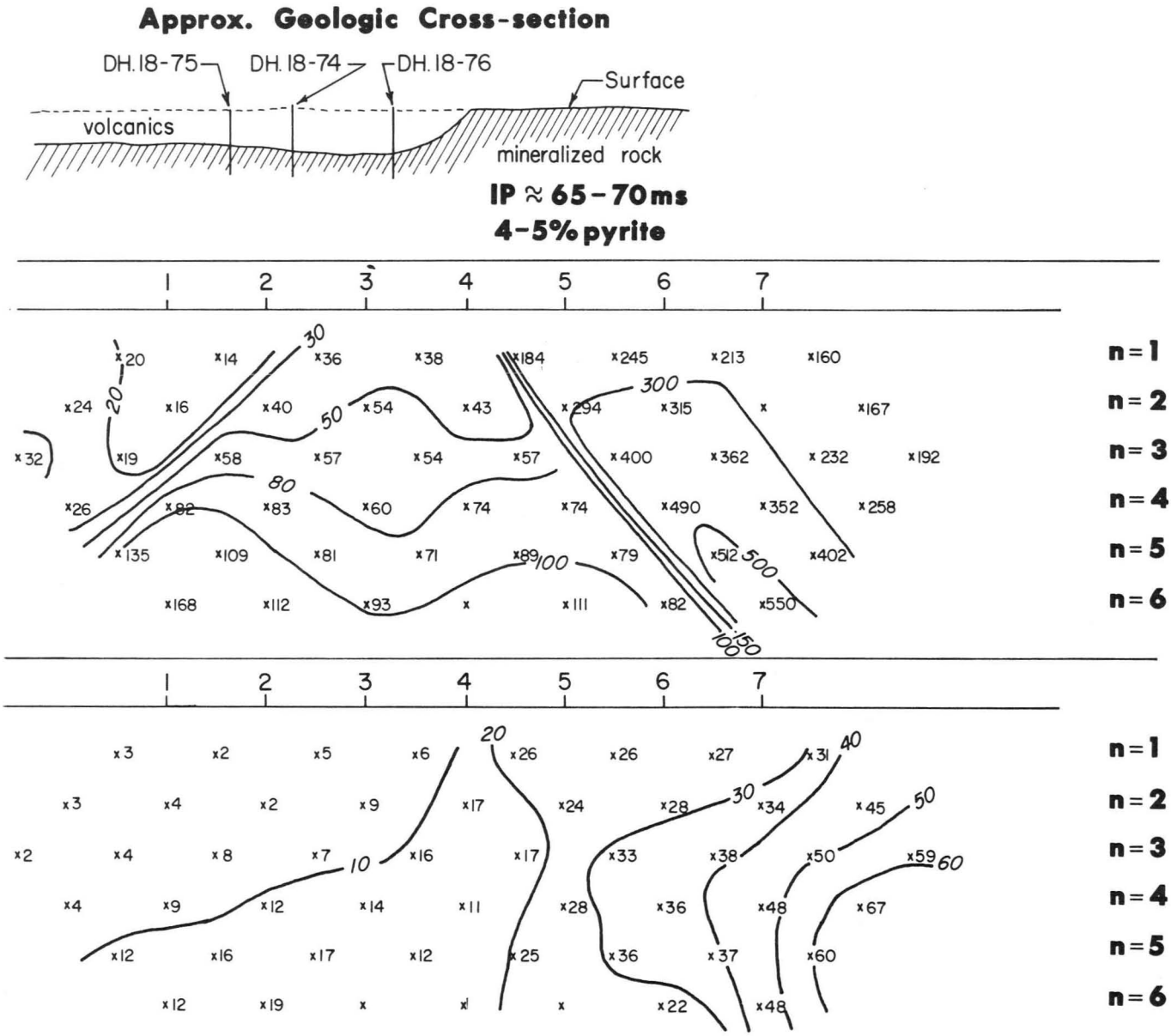


Fig. 13. IP resistivity profile, dipole-dipole array, Silverbell area. Depth to sulfide mineralization only 400 to 500 feet; dipole spacing, 1,000 feet.

under ideal non-noise conditions.

More troublesome masking effects of overburden are encountered if the target zone is well fractured and thus has a resistivity lower than the overlying units. In Figure 11, a body is shown, which is well fractured and covered by the same overburden as supposed in Figure 8, that is, 700 feet of volcanic rock and 300 feet of lower resistivity gravel, but the resistivity of the target is now 1/10 that of the uppermost overburden layer. The percent frequency effect (PFE) of the source body is still 10 times that of the overlying volcanic rock, which is 1 percent, and the response of the gravel is 2 PFE. Under these overburden resistivity conditions, the weighting coefficient for the IP response for the upper layer is negative for certain electrode configurations, and this negative contribution of the IP effect of the upper layer will cancel a portion of the response from the target zone. The theoretical pseudo-section for the ideal no-noise condition for this model is shown in Figure 12. Although the body is detectable at very large n values (those of around 10 to 20), these values are impossible to obtain under field conditions.

Noise affects the depth penetration of an IP system only in that it poses some absolute

limits on the electrode spacing of a particular IP survey system. With conventional equipment in the dipole-dipole configuration, this limit is somewhere around 1,500 feet under resistivity conditions frequently encountered in the Southwest. Although this spacing can certainly be increased by the use of more modern techniques, the noise from geological sources is ever present and tends to increase as the spacings enlarge.

In exploring for porphyry copper systems at depths of 1,000 feet or more by the IP method, the search depth of the now-limited electrode array spacing is restricted almost entirely by the resistivity distribution of the media enclosing the porphyry copper target. In cases where these resistivities are uniform and equal to that of the target, the depth of penetration of an IP system can be almost twice the maximum obtainable electrode separation; detection of targets at 2,000 to 3,000 feet would not be unachievable. However, in cases where the resistivity contrast between the target and the overburden material acts to masked the response from the targets, the depth of penetration might be limited to half or third of the maximum electrode spacings and could be as little as 500 feet if conventional gear is used under noisy conditions. In this instance, exploration would have to proceed utilizing some other method. The figures quoted above will change for different electrode arrays and configurations, but the search depth of the dipole-dipole electrode array provides a general guide to the limitations of detectability of porphyry copper occurrences that will be encountered under most circumstances.

It is important to note that the response is significantly affected by the upper layer. In cases where depth of burial is of the order of 1,000 feet and the upper layer is only 100 feet or so thick, one might be tempted to ignore this relatively thin layer, but doing so might introduce serious interpretational problems. As IP target depths increase, it is necessary to analyze with increasing detail the resistivity of the overlying materials and particularly that of the near-surface layers.

An example of the masking of IP effects by a relatively thin cover of conductive overburden is shown in Figure 13, which shows the IP pseudosection corresponding to a geologic section through a mineralized area near Silverbell, Arizona; the dipole-dipole array with 1,000-foot a spacings was used in the survey procedure. The mineralized body, which nearly crops out on the east side of the section, dips under cover and is buried by a little over 300 feet of conductive gravel and volcanic rocks. The strong IP response seen on the east side of the pseudosection almost disappears in the covered area. A proper interpretation of the IP section in this area would certainly reveal the mineralized body, but the change in response for a relatively minor change in depth of cover is quite striking. The a spacing is three times the depth of burial, but the measured anomaly is only slightly better than marginal.

This example illustrates the point suggested by all the above material that there is no set search depth or spacing of IP electrodes that will meet all conditions. Each survey situation must be evaluated within the context of its own characteristics and restrictive conditions, and these conditions must be determined in each particular survey area before the depth penetration of an IP system can be evaluated.

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GEOLOGY AND MINERALIZATION OF THE LIGHTS CREEK STOCK, PLUMAS COUNTY, CALIFORNIA

by

Lester O. Storey[1]

Abstract

The Lights Creek stock is located in northern California about 100 miles northwest of Reno, Nevada. It is within the Sierra Nevada physiographic province near its juncture with the Cascade and Basin and Range provinces. Structurally it is closely associated with Basin and Range-type features. The area is thought to lie within the influence of the Walker Lane structural lineament and may also be affected by the eastward projection of the Mendocino fracture zone.

The Lights Creek stock is of Late Jurassic to early Eocene age and was emplaced as a differentiated satellite of the Sierra Nevada batholith. The stock hosts at least three large porphyry-type copper-bearing zones. These zones are at the site of the old Superior mine and at the newly discovered Sulfide Ridge and Moonlight Valley areas. Geologic reserves at a 0.2% copper cutoff for the Moonlight Valley are estimated at 250 million tons of 0.35% copper. For the Superior mine, the reserves are approximately 100 million tons of 0.33% copper. An undetermined large tonnage of low-grade material in the Sulfide Ridge area is estimated to grade approximately 0.25% copper.

Petrographic studies indicate that the stock is of heterogeneous composition with a granodioritic center grading outwardly to a granitic periphery. The peripheral areas of the stock are also shown to be more fractured, exhibit the most copper mineralization, and have a higher content of potassium feldspar.

There is a most striking association of copper sulfides occurring with tourmaline as intergrowths in veinlets and disseminations. The abundant tourmaline suggests a late pneumatolytic vehicle for at least some of the ore.

There is a lack of characteristic alteration zonal patterns in the Lights Creek deposits. Alteration assemblages of minerals are present locally and occur overlapping in the ore areas; however, strong and discrete zonation is not apparent. The low sulfur content in the ore zones, as well as the possible contribution of late pneumatolytic copper to the ore zones rather than abundant hydrothermal ore, may account for the unusual mineral assemblages at Lights Creek.

It is suggested that the Lights Creek-type of copper occurrences are not easily recognized because of their unique mineral assemblages and that these low-grade types with relatively fresh appearing outcrops could become the orebodies of the future.

Introduction

The Lights Creek stock is located at the northern limit of the Plumas County copper belt in the Diamond Mountains (Fig. 1). The copper belt is about 18 miles long and has a northwesterly trend. It is defined by the Walker mine at the south and the Engels and Superior mines at the north. Numerous other smaller mines and copper showings occur scattered within the zone. The Walker mine, largest of the producers, recorded more than 80 million pounds of copper during about half of its active life between 1922 to 1930 (Smith, 1970). The Engels and Superior mines were jointly operated by the California Engels Mining Company during the years 1916 to 1930. Production from both of these mines was about 161.5 million pounds of copper recovered from 4.5 million tons of ore (Smith, 1970). This indicates an

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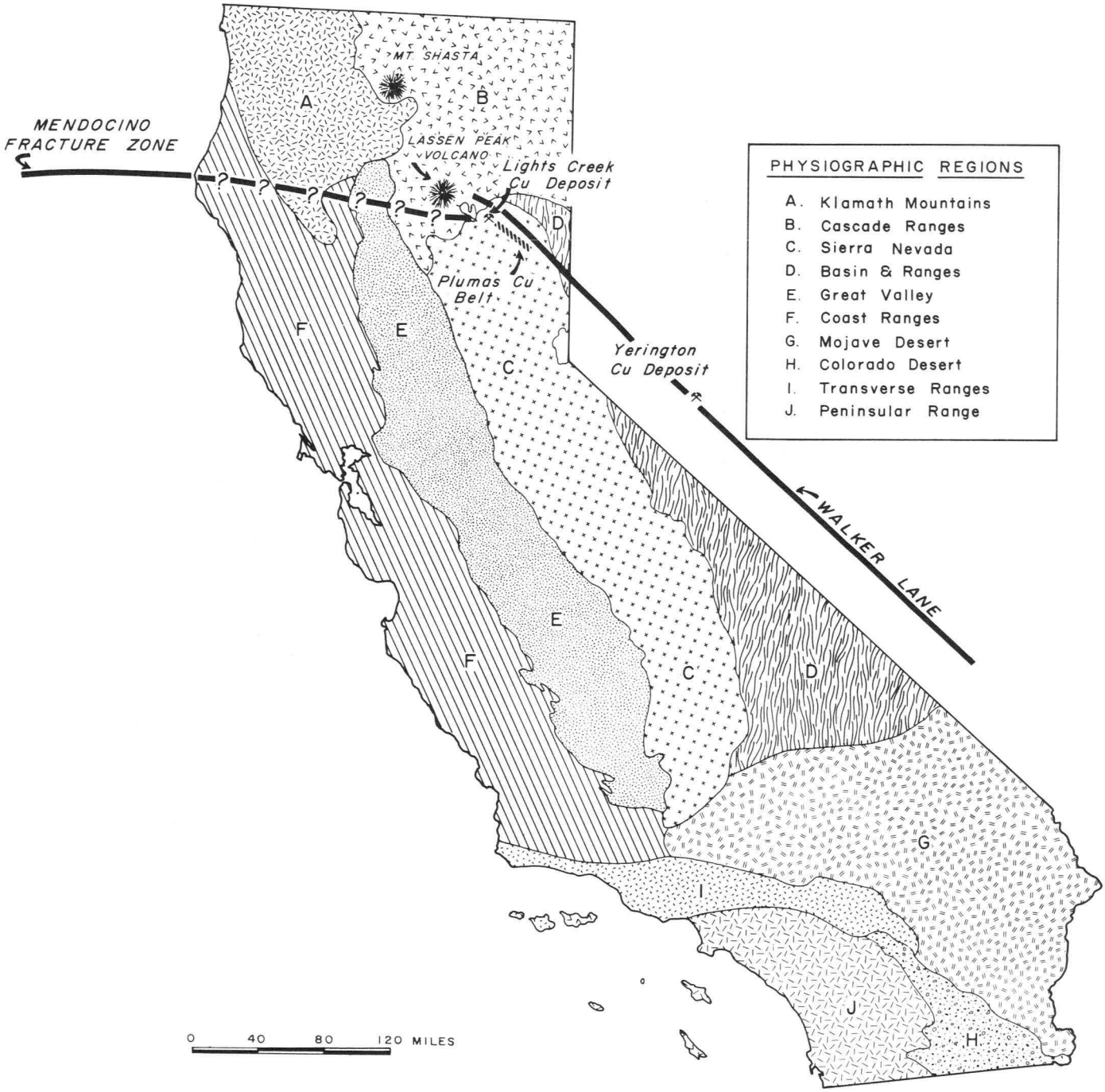

Fig. 1. Location map of the Lights Creek copper deposit

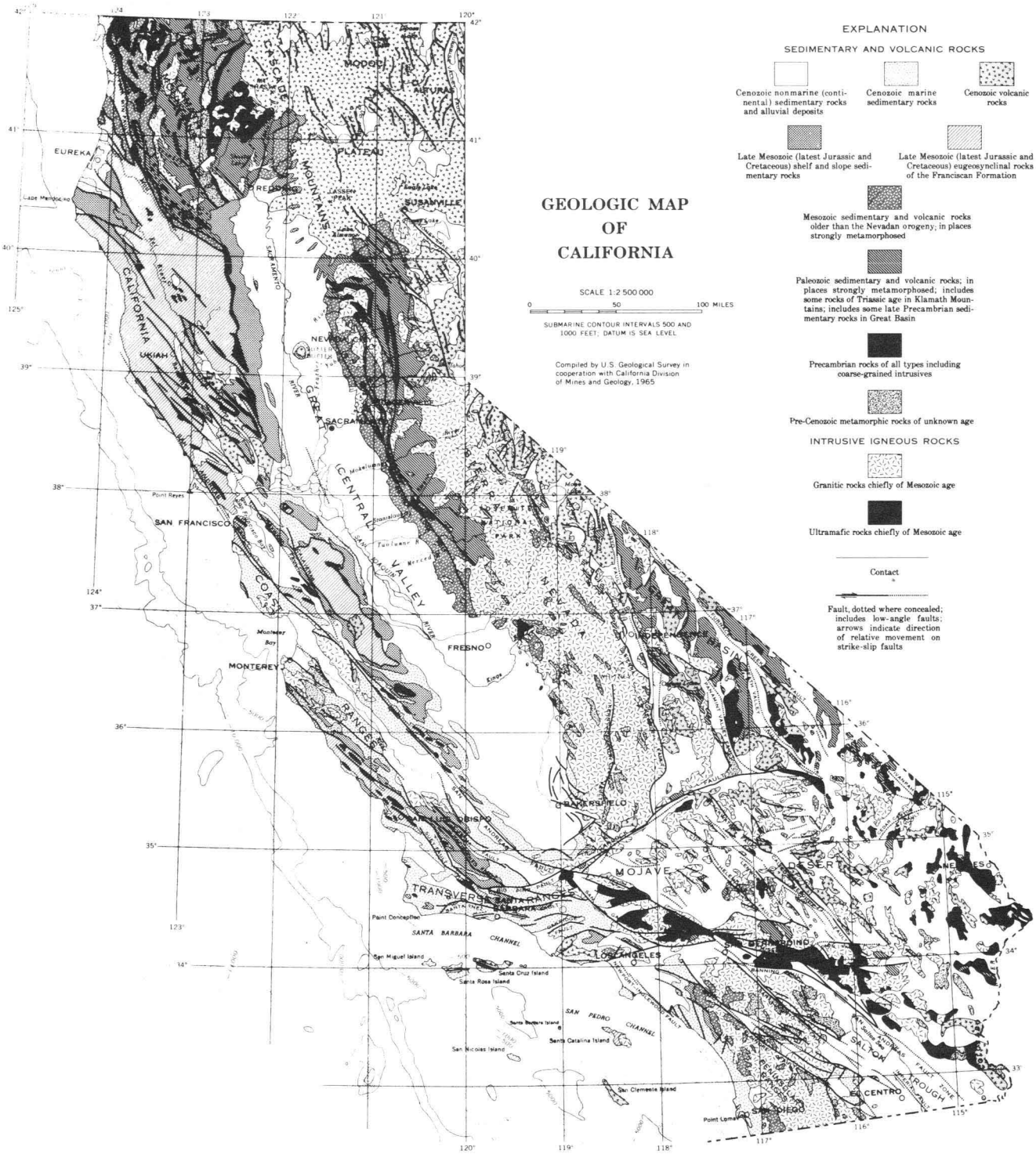

Fig. 2. Geologic map of California—from U.S.G.S. Map I-512

average recovery grade of 1.79% copper. The Superior mine is within the southern boundary of the Lights Creek stock, and the Engels mine is in a gabbroic complex just east of the stock.

Some notable figures in American geology, including Turner, Diller, Tolman, Rogers, Graton, D. H. McLaughlin, C. A. Anderson, and A. Knopf are associated with early investigations of the Engels and Superior mines. Knopf and Anderson (1930) published one of the latest and most definitive accounts of the geology. Additional work by Anderson (1931) and Knopf (1933) were further contributions to the geologic knowledge. The areal mapping of the area by Anderson and the ore deposit geology by Knopf and Anderson provided the foundation for the Placer Amex geologic work. More recently, Smith (1970) and Putman (1972, 1975) have made significant contributions to the knowledge of the distribution of base metals within the stock.

American Exploration & Mining Co., now operating as Placer Amex Inc., began a regional study of the Plumas County copper belt in 1962. Underground workings at the Superior mine were visited and intravein wall rocks were noted to be mineralized. Subsequent sampling of crosscuts indicated large zones of >5% copper. Subsequent geochemical and geologic work delimited the strongly anomalous copper-bearing quartz monzonite stock.

Regional Geologic Setting

The Lights Creek stock lies near the intersection of the Cascade, Sierra Nevada, and Basin and Range provinces. According to Durell (1966) the Sierra Nevada crest is 25 miles to the southwest, and the area is shown within the geographical boundary of the Sierra Nevada province. Lassen Peak is about 50 miles northwest and is considered to be the southernmost volcanic cone of the Cascade province.

The regional structure of this part of northern California is very complex as would be expected from its position near the junction of three geologic provinces (Fig. 2). McMath (1966) summarizes the general features of the area saying it lies athwart the structural axis of the Nevadan orogenic belt characterized here by a northwesterly trending synclinorium composed of Paleozoic and Mesozoic strata. The Sierra Nevada batholith near Lights Creek cuts obliquely into the northeast limb of the synclinorium. The source of this Mesozoic intrusion and its attendant copper-bearing quartz monzonite stock may have been from deep within the eugeosynclinal sediments themselves as suggested by Bateman and Wahrhaftig (1966) or generated in the Benioff zone of subduction as suggested by Hamilton (1969).

Another major crustal feature, which projects just north of the Lights Creek area, is the Mendocino fracture zone. This system is recorded farther west in the Pacific basin and may influence this area.

It is thought that the Walker Lane shear system of right-lateral strike-slip movement projects into the Lights Creek area (Fig. 1). Some of the local structures appear to reflect this influence, and the northwesterly attitude of the Plumas County copper belt could also be a meaningful expression of this trend. According to Pease (1969), the Walker system is at least 100 miles wide, fanning out across the northeastern corner of California into southern Oregon.

Description of the Lights Creek Quartz Monzonite Stock

The Lights Creek stock has a surface area of about seven square miles (Fig. 3). It is thought to have been formed as one of a complex series of multiple intrusive satellites of the Sierra Nevada batholith. It intrudes low-grade metamorphosed Jurassic-Triassic volcanic and sedimentary rocks. The main Sierra Nevada batholith, east of the stock in the vicinity of Honey Lake, has been dated by the potassium-argon method as in the range of 97.4 to 101 m.y. (Evernden and Kistler, 1970). Nonmarine, gently dipping Eocene sedimentary rocks cover some northwestern portions of the stock, and they correlated with Diller's (1908) auriferous gravels of the same age. Therefore, the age of emplacement and subsequent mineralization of the stock is considered to be within the interval of Early Cretaceous to Paleocene. Most likely the age of mineralization would be closer to the intrusive age and would approximate 100 m.y., thus having the same general age as the copper deposit at Yerington, Nevada.

Early work by Anderson (1931) has defined five distinct Sierra Nevada batholith differentiates in the Lights Creek area. These are, in order of their emplacement from oldest to youngest:

1. Engels mine gabbro (main host to high-temperature Engels mine copper deposit).
2. Quartz diorite (also host to Engels mine ore).
3. Granodiorite (main batholith, nonmineralized).
4. Quartz monzonite (host to porphyry-type copper occurrences of intermediate temperature).
5. Coarse-grained granite (non-copper bearing with rare molybdenum occurrences).

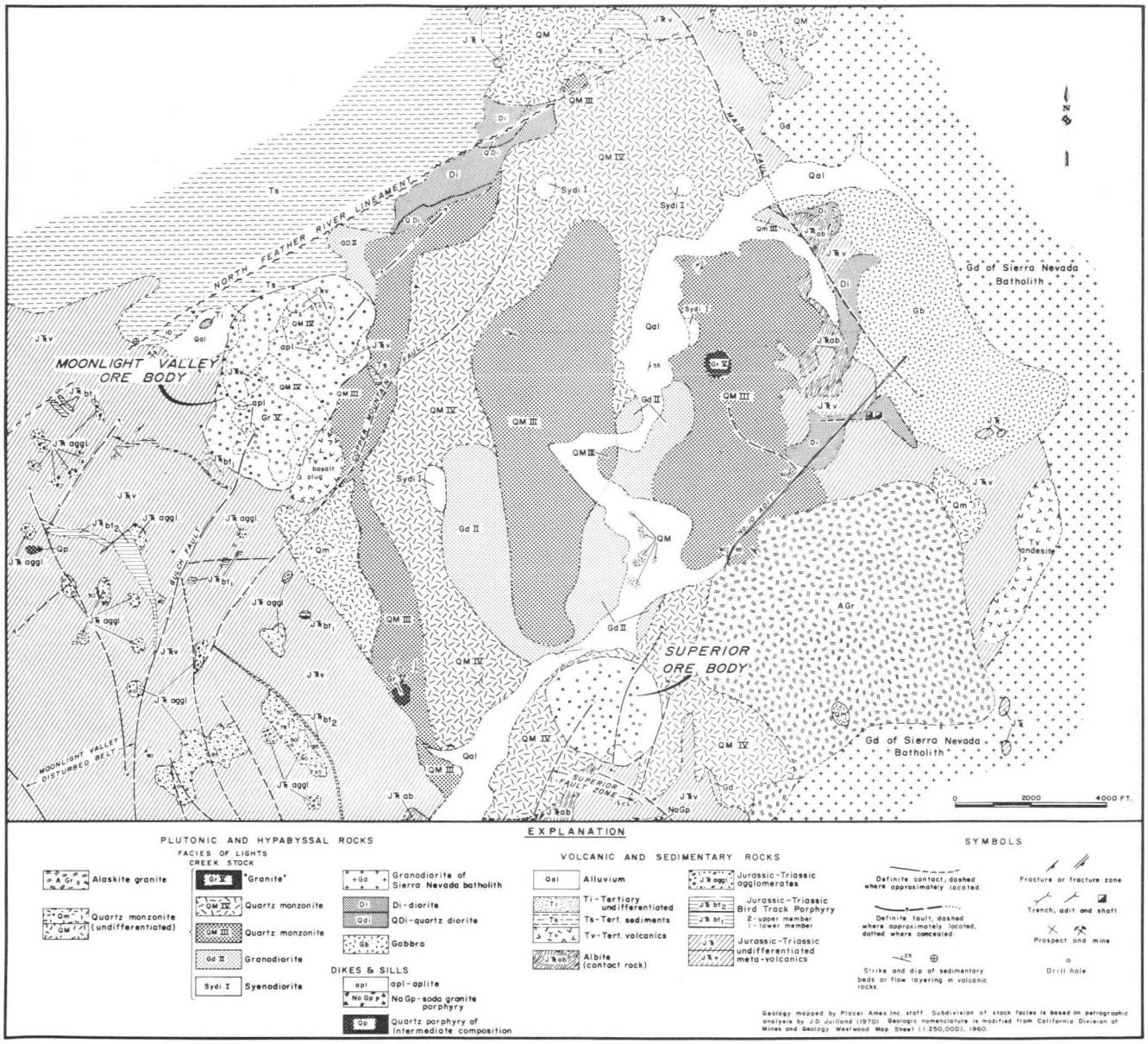

Fig. 3. Geologic map of the Lights Creek stock, Plumas County, California

The quartz monzonite is the most heterogeneous in overall make-up of any of the segregated intrusive bodies. The overall aspect of the quartz monzonite is one of angular blocky outcrops (Fig. 4). These outcrops form conspicuous cliffs in the area (Fig. 5).

A study of the Lights Creek stock by Juilland (1970) deals with the complex chemistry of the stock. He examined thin sections and polished sections, including samples taken from underground workings and drill core. By plotting the potassium feldspar to plagioclase feldspar ratio at various sample points and contouring the values he described several compositional zones within the stock. These zones range according to their modal analysis from granite through quartz monzonite to granodiorite (Fig. 3). He further points out a strong relationship between the potassium-rich areas of the stock and the better copper mineralization.

The chief minerals of the stock are plagioclase, K-feldspar, hornblende and soda amphibole, quartz, tourmaline, epidote, magnetite, and ilmenite with minute amounts of chalcopyrite, bornite, and pyrite. The rock is equigranular, fine to medium crystalline with few coarse crystalline zones. Aplitic and porphyritic textures are also recognized locally, especially in the Moonlight Valley area. Overall, the rock is weakly magnetic but in localized areas magnetite can be abundant, especially in the mineralized zones. Table 1 shows the

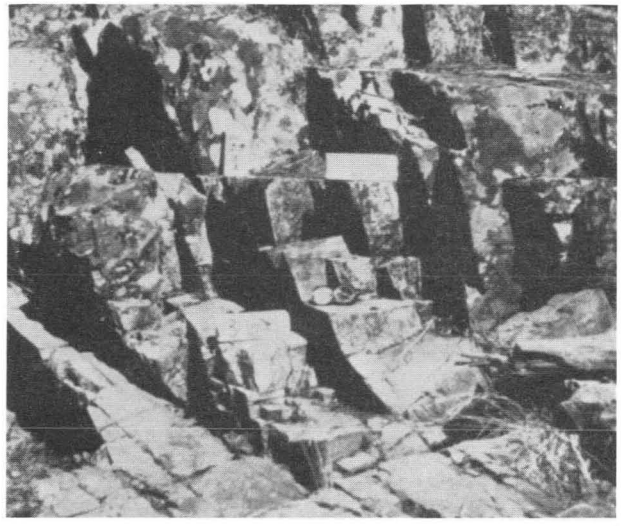

Fig. 4. Quartz monzonite showing angular blocky outcrops

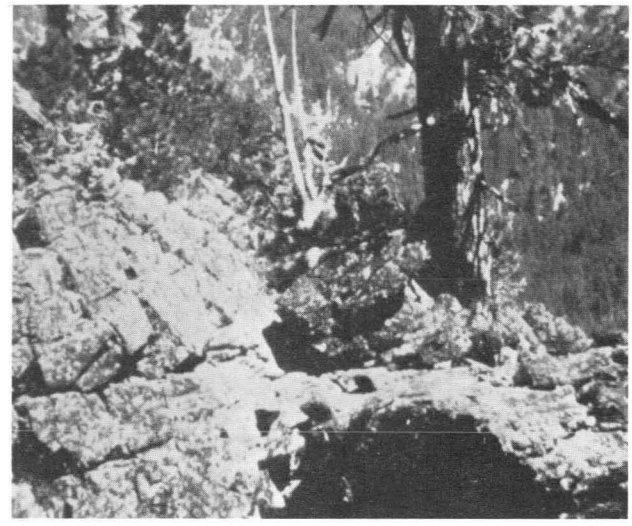

Fig. 5. Quartz monzonite forms prominent cliffs in the area

generalized composition of the stock after Juilland (1970).

Table 1. Lights Creek Stock—After Juilland (1970)

	Volume Percent		
Mineral	Maximum	Minimum	Average
K-feldspar	56.2	20.4	32.9
Plagioclase	42.0	23.0	31.4
Quartz	43.2	18.1	21.4
Totals	94.7	80.5	85.7
Mafics	27.7	0.4	11.0
Metallics	12.2	0.3	3.3

Mapping in the stock area has shown three dominant structural trends, which are northwest, northeast, and north-south (Fig. 3). Mineralization is most commonly associated with the northeast and north-south structural directions. Northwest structures commonly enhance the mineralization and/or cut it off.

Copper Mineralization in the Stock

The Lights Creek stock appears to be unique in the area in that it hosts porphyry copper-type mineralization. Putman (1975) shows by statistical analysis that copper mineralization has been introduced on a large scale and that it is not merely a small-scale segregation of magmatic-stage constituents. He further suggests a largely magmatic source for the metals in the stock.

At least three zones of copper mineralization have been delimited, two of which contain economically significant grades of copper. Over 200,000 feet of diamond drilling and 3,550 feet of rotary drilling have helped to define these zones. The site of the old Superior mine is the southernmost of the areas, having an estimated geologic reserve of 100 million tons of 0.33% copper at a 0.2% copper cutoff. The Moonlight Valley deposit, 1.9 miles northwest of the Superior deposit, is estimated to have a geologic reserve of 250 million tons grading 0.35% copper at a 0.2% copper cutoff. The Sulfide Ridge area, 1.7 miles northeast of the Superior mine, indicates an undetermined large tonnage of material, which could average 0.25% copper.

These three major mineralized zones occur entirely within the quartz monzonite stock near its contact with the older intruded rocks. Each of these areas show a greater degree of fracturing than elsewhere within the stock. Mineralization is found as disseminations and fracture fillings. Juilland (1970) has postulated at least two generations of copper mineralization. The first is of magmatic stage origin no later than pneumatolytic, while the second is of hydrothermal origin and has taken place after crystallization of the stock when fractures were formed and sustained.

Alteration of the Quartz Monzonite

Typical porphyry copper-type alteration zoning as illustrated by Lowell and Guilbert (1970) is nonexistent. Recognizable hydrothermal alteration of the Lights Creek deposits is unimpressive compared with that accompanying most porphyry copper deposits in the southwestern United States.

Of the three mineralized zones, the Moonlight Valley deposit resembles other porphyry systems. However, sericitic and argillic alteration occur most typically only in the fracture zones and not pervasively throughout the rock. Chlorite is apparent at each of the mineralized areas and has formed at the expense of some of the ferromagnesian minerals. Although the stock is more potassium-rich in the Moonlight area, Juilland (1970) considers only the K-feldspar that occurs in veinlets to be positively hydrothermal and that which occurs as disseminations to have formed during crystallization of the magma (Fig. 6). If this is correct, potassic alteration would also be considered as minimal. However, the nearly complete absence of primary biotite in the stock has led Juilland to further conjecture that it may have been completely destroyed by late deuteric alteration from K-feldspathization and he cites the work of Hemley (1959) and Rutherford (1969) to support this hypothesis.

Tourmaline is the most remarkable mineral associated with the copper deposition. It is found principally as the iron-rich dark variety, schorlite, in both fracture vein fillings and as sunburst blebs throughout the rock. Interesting intergrowths with bornite and chalcopyrite are often associated with both forms of tourmaline (Fig. 7). Quartz commonly occurs with tourmaline in the mineralized veinlets. Epidote occurs throughout the stock in patches and veins and is particularly abundant within the zones of sulfide mineralization. It appears to increase in density closer to the contacts with the intruded rock or where xenoliths are abundant in the quartz monzonite.

Pyrite is relatively scarce in the Lights Creek stock. The predominant sulfides of the system are chalcopyrite and bornite. Magnetite and hematite are present as disseminations and in veins. However, hematite, generally occurring as specularite, is much more prominent in the Moonlight Valley area than magnetite. Specular hematite appears to be more pervasive on the southwest end of the Moonlight Valley deposit where it plunges under the older volcanic cover. This occurrence may represent a flooding front of iron out from the copper mineralized center into the overlying volcanic rock. The absence of pyrite and abundance of hematite at Moonlight Valley is evidence of a low sulfur environment and probably would account for the lack of supergene clay alteration.

Copper Occurrences

Moonlight Valley Deposit

The main ore minerals occurring in the Moonlight Valley deposit are bornite and chalcopyrite with lesser amounts of covellite and chalcocite. Important gangue metallic minerals found with the ore are magnetite, hematite, and lesser amounts of pyrite. Nonmetallic vein minerals accompanying the copper mineralization are quartz, tourmaline, siderite, dolomite, calcite, epidote, chlorite, and rarely actinolite. Typically, there are centers with best copper mineralization which show abundant bornite and minor amounts of chalcocite. As the grade decreases, chalcopyrite increases and bornite decreases. Farther away from the

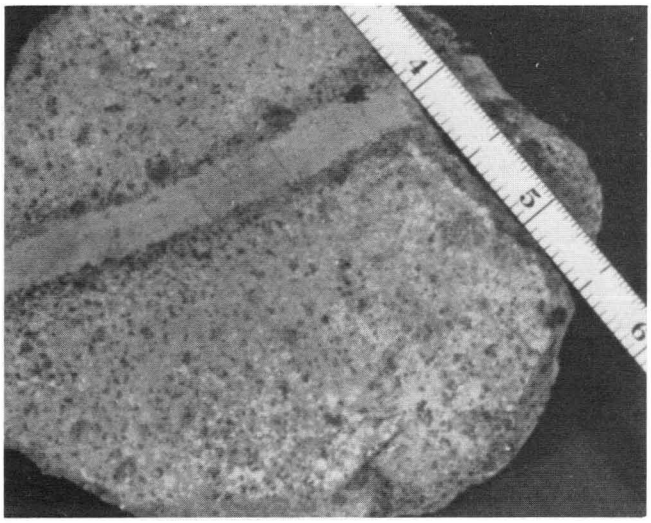

Fig. 6. Veinlet in quartz monzonite showing hydrothermal K-feldspar

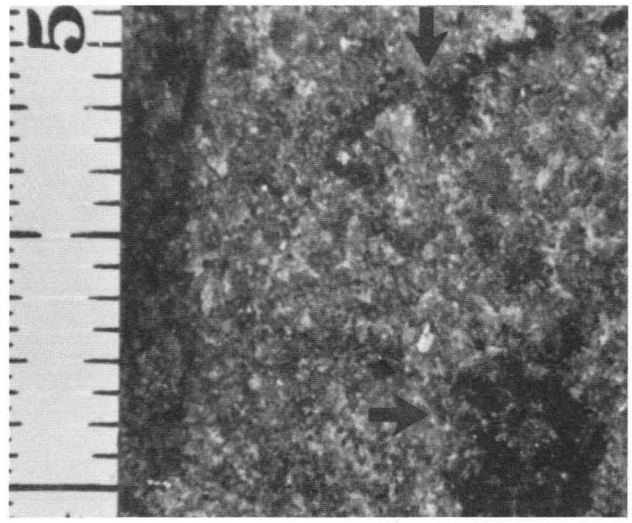

Fig. 7. Quartz monzonite specimen showing an interesting intergrowth of bornite and chalcopyrite associated with tourmaline

high-grade centers, the appearance of increased pyrite indicates even lower grades. Chalcopyrite occupies an intermediate position and perhaps makes up the greatest bulk of the ore. The chalcocite, with few exceptions, is believed to be hypogene. Under the microscope it appears to form exsolution textures with bornite and to replace bornite (Bryner, 1972). Bornite and chalcopyrite also commonly exhibit exsolution features (Bryner, 1972).

Other minerals occurring in very minor amounts are pyrrhotite, molybdenite, sphalerite, galena, tetrahedrite-tennantite, and luxonite. None of these minerals contributes economically recoverable metals with the exception of possibly the tetrahedrite-tennantite, as silver values for the deposit average ± 0.1 oz per ton.

Very little supergene enrichment has occurred at the Moonlight Valley deposit. Surface exposures and the tops of some holes show meager oxidation and leaching with limited limonite, manganese oxides, malachite, azurite, chrysocolla, and native copper. Sparse sooty chalcocite is found in some holes but certainly does not express a significant enrichment to the orebody.

Although it is difficult to map structure in the Moonlight Valley area because of lack of surface outcrops, it is quite evident from drillhole information that the better copper mineralization is closely associated with a higher degree of shattering and fracture fillings. Strong structural control for the ore is very apparent. The deposit is broadly arch shaped, conforming to a domelike feature with a long dimension northeast-southwest (Fig. 8). From a limited few deep drill holes it is indicated that the orebody has several roots, with the largest and most persistent under the volcanic cover to the southwest. Geologic surface mapping has suggested a dome in the older volcanics conformable to both the Superior mine and the Moonlight Valley ore zones. Bryner (1972) postulated the occupancy of these domal structures by local apophyses into the roof by the stock. This would mean that these deposits are positioned in the uppermost portions of the stock.

Strong northeast, northwest, and north-south sets of shears in the Moonlight Valley area appear to be important for the overall structural plumbing system for the ore; however, the local brecciation and crackling which is apparent in the best ore zones may be closely related to the plutonic emplacement, perhaps as late resurgence into a semiconsolidated rim. This is substantiated by the fact that there is much less fracturing developed toward the center of the stock than near its margin.

Superior Mine

The Superior Mine mineralization is thought to be of a higher temperature of formation than Moonlight Valley. Anderson (1931) has given good descriptions of the Superior orebody. He has considered the ore-forming minerals to have been introduced under hydrothermal conditions into previously formed higher temperature pneumatolytic gangue minerals.

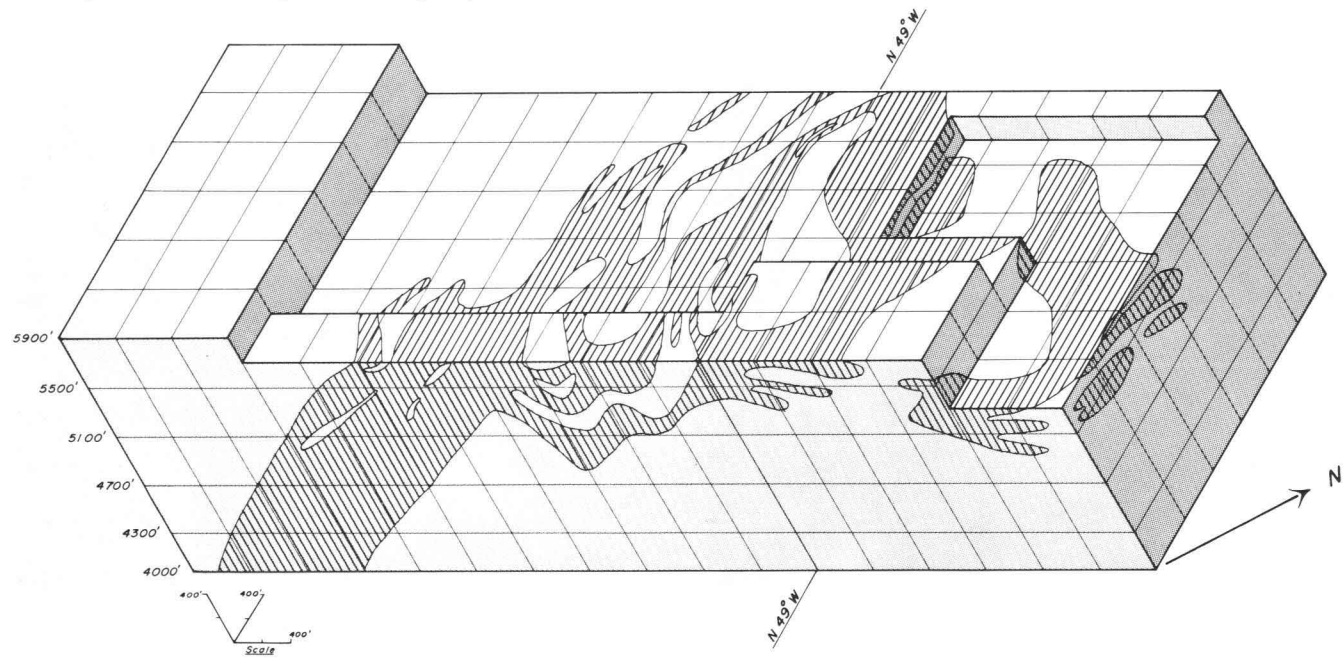

Fig. 8. Block diagram of the Moonlight Valley orebody (from Moonlight Valley drill sections)

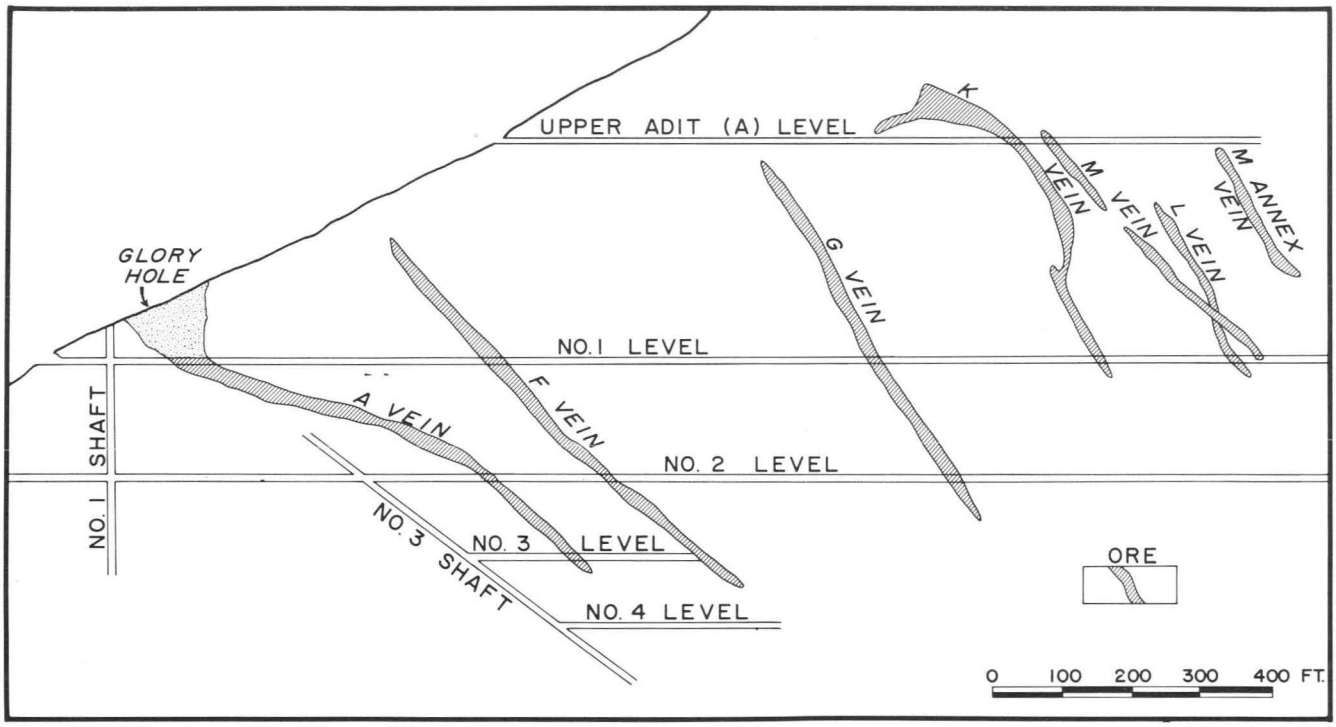

Fig. 9. Diagrammatic cross section of the Superior mine—after Anderson (1931)

The Superior deposit occupies a stockwork around seven parallel, northerly striking, easterly dipping (8 to 10 feet thick) vein zones with accompanying sheeting and brecciation (Fig. 9). Strong N. 30° E. shear zones dipping 55° E. limit the high-grade veining in an east-west direction. Mineralization is enhanced and/or cut off by northwest-striking, southwest-dipping shear zones superimposed on the vein system. The typical mineralized vein zone contains chiefly chalcopyrite with smaller amounts of bornite, magnetite, and pyrite in a dark gangue of black schorlite, green mica, actinolite, quartz, epidote, chlorite, sericite, apatite, titanite, and siderite. Intervein wall rock is also mineralized with disseminations and fracture fillings.

Magnetite is much more prevalent in the Superior area than at Moonlight Valley; however, specularite, which is very strong at Moonlight Valley, is nearly nonexistent at the Superior mine.

Sulfide Ridge Deposit

The Sulfide Ridge copper occurrence is more like the Superior mine than the Moonlight Valley deposit. However, the only subsurface information available for the area is from diamond drill cores. Outcrops show the strong influence of structural control for the mineralization (Fig. 10).

Summary and Conclusions

In summary, it can be stated that the Lights Creek quartz monzonite stock contains large concentrations of copper. These copper-bearing zones are of sufficient cohesion to qualify them as porphyry copper systems. However, some of the features commonly associated with the copper porphyry deposits of the southwestern United States are missing at Lights Creek. Most conspicuously absent are

Fig. 10. View looking east of Sulfide Ridge

the zonal alteration assemblages usually found with such a system. A combination of low sulfur and pyrite with some pneumatolytic rather than hydrothermal introduction of at least a portion of the copper sulfides may have helped to obscure more pervasive alteration. Also, very little supergene activity together with minimal surficial clay alteration has given outcrops a relatively fresh appearance. Some of these and other unique features at Lights Creek may indicate more subtle mineral assemblages that perhaps will lead to copper deposits in the future. The successful exploration results at Lights Creek should encourage the pursuit of nonconventional copper systems. Perhaps this will result in additional new districts being found.

Acknowledgments

I would like to thank Placer Amex Inc. for allowing me to present this paper. Particularly, I would like to acknowledge H. J. Matheson, Vice President of Exploration, and J. B. Bush, Manager of Exploration, for their help and encouragement in the preparation of this paper. Recognition should also be given to C. B. Gillette for critical review and suggestions for this manuscript.

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CONTROLS OF OXIDE COPPER MINERALIZATION, MACARTHUR PROPERTY, LYON COUNTY, NEVADA

by

David A. Heatwole [1]

Abstract

The MacArthur deposit is an outcropping, oxidized porphyry copper occurrence located approximately 5 miles north of Anaconda's Yerington mine, Lyon County, Nevada. A significant mineral reserve was developed on the property in 1971-72.

The Jurassic quartz monzonite host rock of the deposit is intruded by two varieties of quartz monzonite porphyry and a rhyolite, also Jurassic in age. Tertiary hornblende andesites constitute the youngest rocks in the deposit. All of the intrusive rocks, except the older quartz monzonite, occur as northwest-trending dikes which dip moderately to the north.

Sulfide copper mineralization accompanied the intrusion of the older quartz monzonite porphyry. The alteration pattern associated with the Jurassic quartz monzonite porphyry was strongly influenced by the northwest fracture pattern and generally consists of a phyllic zone to the north and west, a very weakly potassic central zone, and a strong albite zone to the east.

Oxide copper values occur in three distinct mineral assemblages: (1) green copper oxides, (2) black copper wad, and (3) dark-brown limonites. Copper and iron are crudely zoned in the oxide mineralogy with a high iron to copper ratio in the north and west parts of the orebody and low iron to copper oxide assemblage to the east.

Higher grade oxide copper zones on the MacArthur property are erratic and difficult to project. Although poorly defined, several geologic features appear to control the grade distribution:

Major Controls

1. Primary grade distribution—higher grade oxide zones occur where the original sulfide grade was higher.
2. Exotic copper or oxide enrichment—supergene copper from the peripheral phyllic zone has moved laterally to enrich the low-grade porphyry copper center.

Minor Controls

1. Superleach zone—copper values leached from the present bedrock surface are redeposited several feet below.
2. Andesite dikes—unpyritized andesite dikes absorb exotic copper.
3. Fracture pattern—strong northwest-trending fracture pattern imparts similar trends to the grade zones.
4. Oxidized enrichment—deep zone of oxide mineralization immediately above the top of sulfide may represent an oxidized enrichment blanket.

Introduction

The MacArthur deposit is located in northwestern Nevada about 50 miles southeast of Reno, near the towns of Yerington and Weed Heights. The deposit is situated about five miles north of The Anaconda's Company's Yerington mine (Fig. 1). A mineral reserve was developed on the property by Anaconda geologists during the period 1971-72 as part of a district exploration program to find oxide ore that could be treated by the Yerington Mines oxide plant.

Mining claims were staked on the MacArthur property during the 1930s by local pros-

[1] The Anaconda Company, Tucson, Arizona 85726

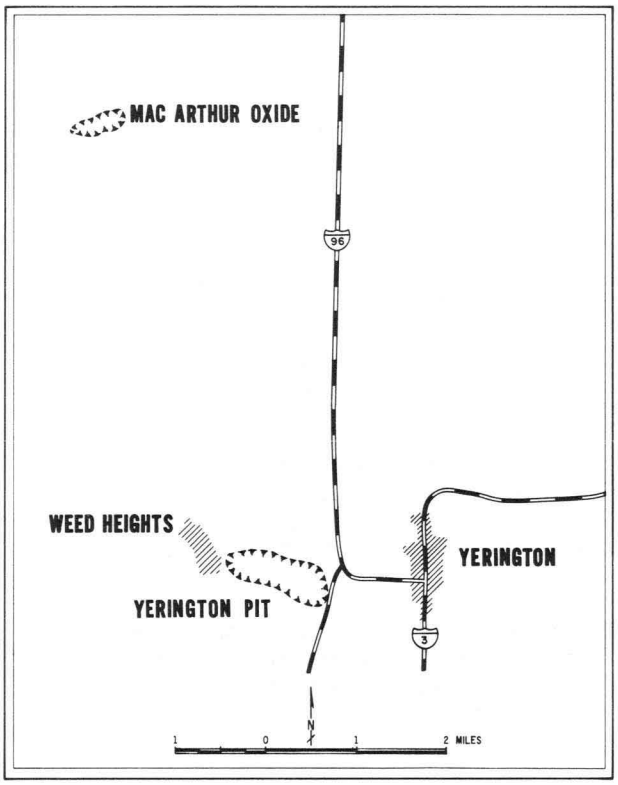

Fig. 1. Location map, MacArthur oxide deposit

pectors and several small shipments of hand-cobbed, high-grade oxide ore were made during this period. In 1950, the U.S. Bureau of Mines dug a series of trenches on green copper oxide occurrences and drilled eight diamond drill holes. During the period 1954 to 1971 the property was optioned by at least four major mining companies, including Anaconda. Over 60 holes were drilled on the property during this period; and approximately half of these drill holes are located within the known MacArthur orebody.

Recent Exploration

A mineral reserve was developed on the property in 1971-72 by a combination of detailed geologic mapping, systematic trenching, and improved drilling technology. The initial exploration work consisted of geologic mapping at the scale 1" = 200' and a compilation of existing data on the property. The preliminary geologic mapping delimited a broad zone of "glass or beer-bottle" limonite, which is known to represent oxidized chalcopyrite mineralization in the Yerington district's leached cappings. ("Glass-limonite" is a term used to describe resinous, dark-brown goethite.) The limonite mapping proved to be a very effective exploration tool; Figure 2 illustrates the zone of glass limonite as defined by the initial mapping and the outline of the pit which was designed to mine the Macarthur oxide mineralization.

The glass limonite zone was subsequently trenched and assayed. The trenching program delimited an outcropping area approximately 1000 x 2500 feet that assayed approximately 0.25% copper and contained erratic zones of higher grade. Both the grade zones and the geology projected into shallow covered areas to the north and east of the outcrops.

It was recognized early in the MacArthur evaluation that because of the nature of the oxide mineral occurrences (90% on fractures) that a large part of the copper values would be ground up and lost by conventional drilling techniques due to pulverization and dissemination by the drilling fluid. Screen analysis of drill cuttings showed that 40 percent of the copper values were contained in the - 50 mesh portion of the sample, which represented 28 percent of the weight of the samples. It was obvious that the loss of fine material resulted in a disproportionate loss of copper values. In order to obtain an accurate sample, Anaconda's Mining Research Department designed a sample collection system that collects 100 percent of the discharge from the percussion drill.

Over 280 vertical and angle holes, to an average depth of 200 feet, were drilled on the property. Both percussion and rotary drilling rigs were employed. The drilling and surface sampling defined approximately 13 million tons of +0.4% Cu mineralization.

Rock Types and Alteration

The host rock for the MacArthur oxide deposit is a quartz monzonite of Jurassic age (161 m.y., K-Ar). The quartz monzonite is intruded by northwest-trending dikes of quartz monzonite porphyry (Fig. 3). The older of these porphyries has prominent biotite phenocrysts and disseminated chalcopyrite. The younger porphyry has prominent hornblende phenocrysts and does not appear to influence copper grade patterns. A northwest-trending dike of rhyolite cuts the hornblende-rich quartz monzonite porphyry. Although the porphyries at the MacArthur property have not been dated, similar porphyries elsewhere in the Yerington district have yielded Jurassic dates (141 m.y., K-Ar).

Numerous northwest-trending dikes of hornblende andesite cut across the older intrusive rocks. Similar andesites elsewhere in the Yerington district have been mapped intruding Tertiary rocks.

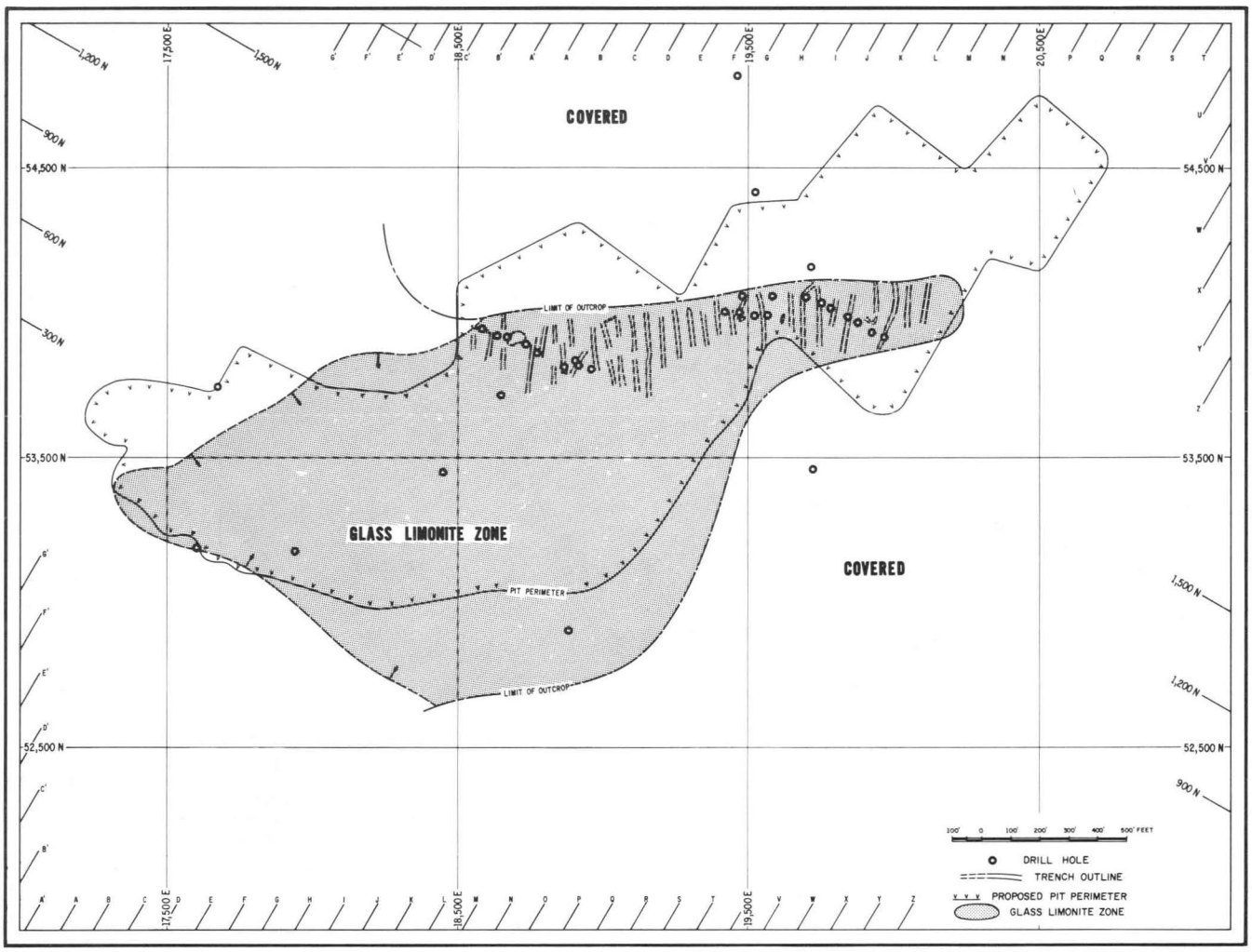

Fig. 2. Surface map of glass limonite zone and proposed pit outline, MacArthur oxide deposit

The following is a brief description of the rock types, listed in order of relative age (oldest to youngest).

Quartz monzonite is a medium to coarsely crystalline, equigranular rock with hornblende as the dominant mafic.

Biotite quartz monzonite porphyry is characterized by abundant quartz eyes, K-feldspar phenocrysts, and biotite phenocrysts in an aphanitic matrix. The northwest-trending dikes of biotite quartz monzonite dip 30°-40° N.

Hornblende quartz monzonite porphyry is texturally similar to biotite-rich quartz monzonite porphyry, but it has only rare quartz eyes, no K-feldspar phenocrysts and hornblende is the dominant mafic mineral. The northwest-trending dikes of hornblende quartz monzonite dip approximately 60° N.

Rhyolite is similar in composition to hornblende quartz monzonite porphyry except that it contains only rare phenocrysts. The dikes of rhyolite, which vary in dip from 75° N. to vertical, show sharp contacts with the hornblende quartz monzonite porphyry.

Pyritic hornblende andesite is a porphyritic andesite with prominent hornblende phenocrysts and 1-2% disseminated pyrite. The pyritic andesite dikes generally dip steeply northward.

Andesite dikes are usually porphyritic and occur both with and without hornblende phenocrysts. These dikes show little evidence of primary sulfide mineralization. The dips vary from steep to horizontal.

The alteration pattern at the MacArthur is very stripy, apparently strongly influenced by the northwest fracture pattern. The alteration zoning is as follows:

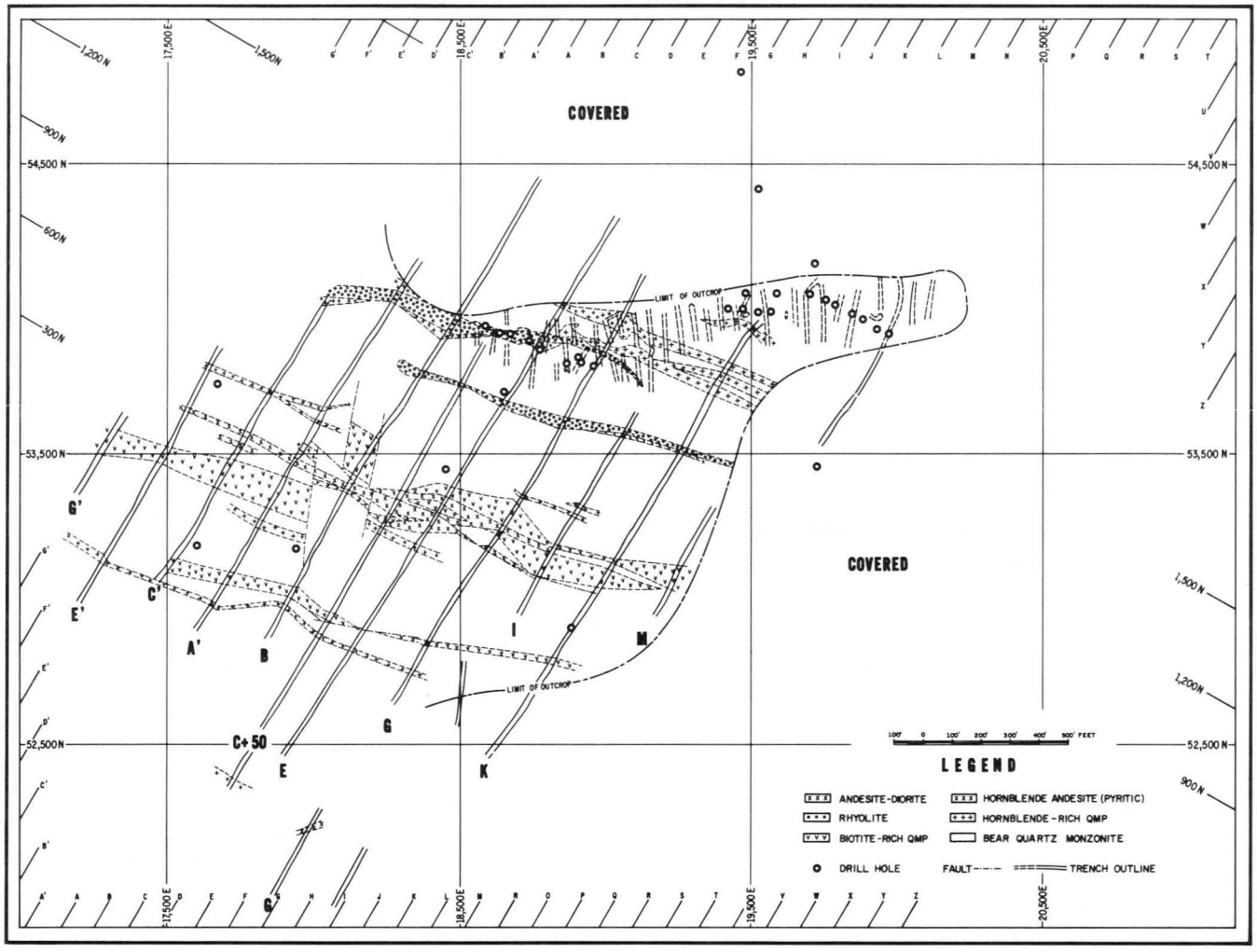

Fig. 3. Surface geology, MacArthur oxide deposit

1. The western phyllic zone is defined by stripy feldspar destructive alteration where plagioclase is partially altered to sericite, K-feldspar is fresh to partially altered to sericite and the mafic minerals are completely altered to sericite and clay. Based on the mapping of the drill cuttings, the phyllic alteration zone extends to the east along the northern edge of the oxide ore zone (Fig. 7).

2. The central zone is unaltered except for minor potassic alteration in the form of local biotization of hornblende.

3. The eastern albitic zone is characterized by the stripy albitization of both plagioclase and K-feldspar. The albitization is more pervasive to the east.

Copper Oxide Mineralogy and Distribution

Oxide copper values occur in three distinct mineral assemblages:

1. Green copper oxides—dominantly blue and green chrysocolla with minor amounts of malachite, azurite, and other unidentified green oxides.

2. Black copper wad—a sectile, amorphous mixture of copper-iron-manganese oxides and silica, which frequently is coated with scales of blue copper minerals.

3. Dark-brown iron oxides—dominantly goethite, rock mineralized with only brown limonite can contain up to 0.3% Cu. The dark-brown limonites contain copper only if they occur in rocks with fresh feldspar; similar limonites in altered rocks do not contain significant copper values.

The distribution of copper and iron in the oxide mineralogy shows a crude zoning with the high iron oxides, goethite and wad, more

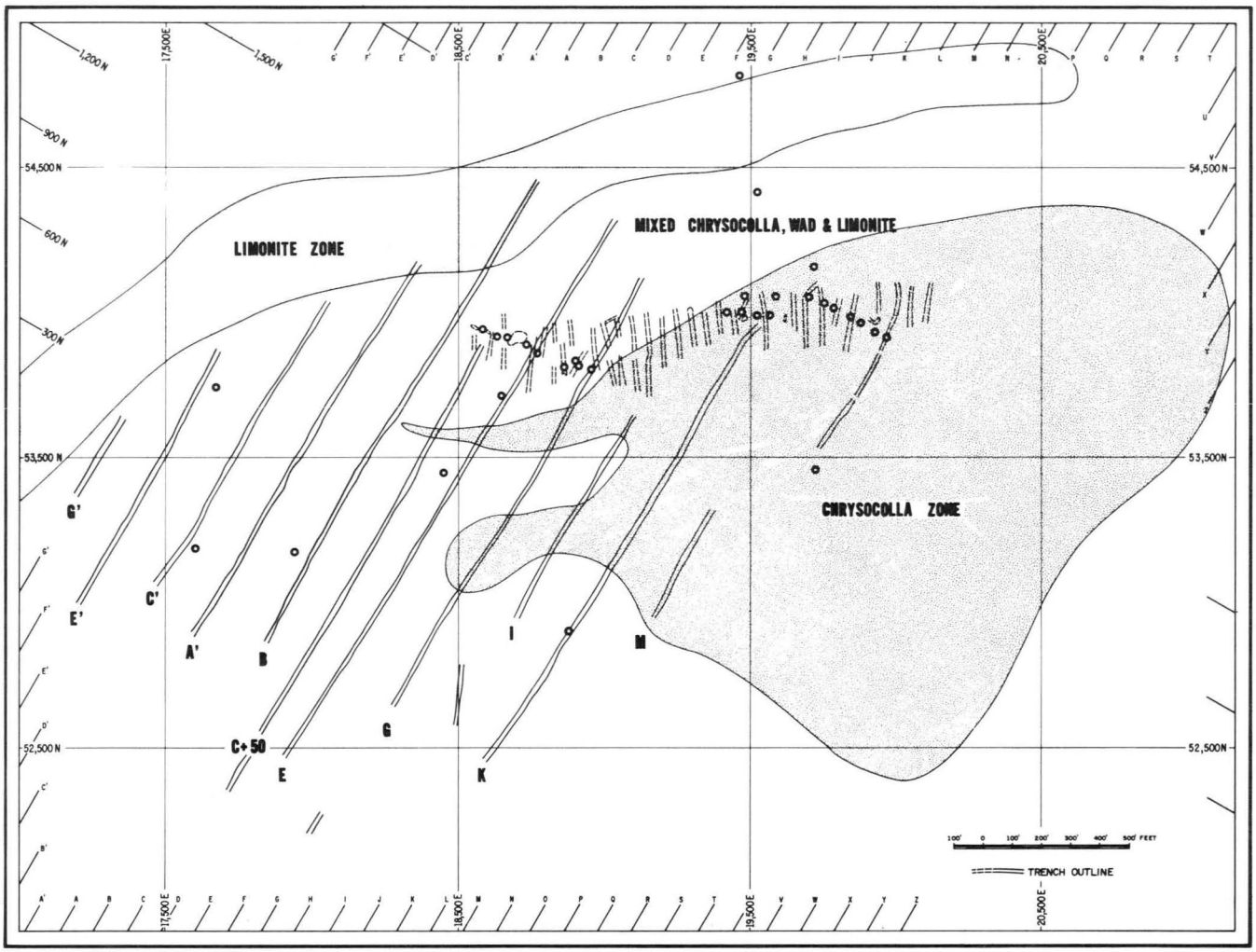

Fig. 4. Distribution of copper-iron oxides, MacArthur oxide deposit

prevalent to the northwest, while chrysocolla is the dominant copper mineral to the southwest (Fig. 4). Along the northern edge of mineralization the zone of high iron oxides occurs farther east paralleling the phyllic alteration zone. This zoning of iron is probably due to the primary sulfide assemblage because the western part of the area was originally high in pyrite. The chrysocolla zone is coincident with the glass limonite zone and probably represents the oxidation of a chalcopyrite-rich primary sulfide assemblage.

Controls of Oxide Copper Mineralization

Zones containing +0.4% Cu on the MacArthur property are erratic and difficult to project for any distance. Although poorly defined, several geologic features that apparently control the grade distribution were used successfully to project grade zones. The difficulty of recognizing grade controls in an oxide copper deposit results from primary grade zones being "washed out" by supergene processes.

The geologic factors influencing the grade distribution on the MacArthur property are:

Major controls—(1) primary grade distribution, and (2) exotic copper or oxide enrichment.

Minor controls—(1) superleach zone, (2) andesite dikes, (3) fracture pattern, and (4) oxidized enrichment.

Figures 5 and 6 illustrate the effect of the primary grade pattern. The gentle north dip of the +0.5% Cu zone parallels the dip of a biotite quartz monzonite porphyry dike. The higher grade oxide copper apparently is due to chalcopyrite mineralization, which accompanied the biotite quartz monzonite porphyry.

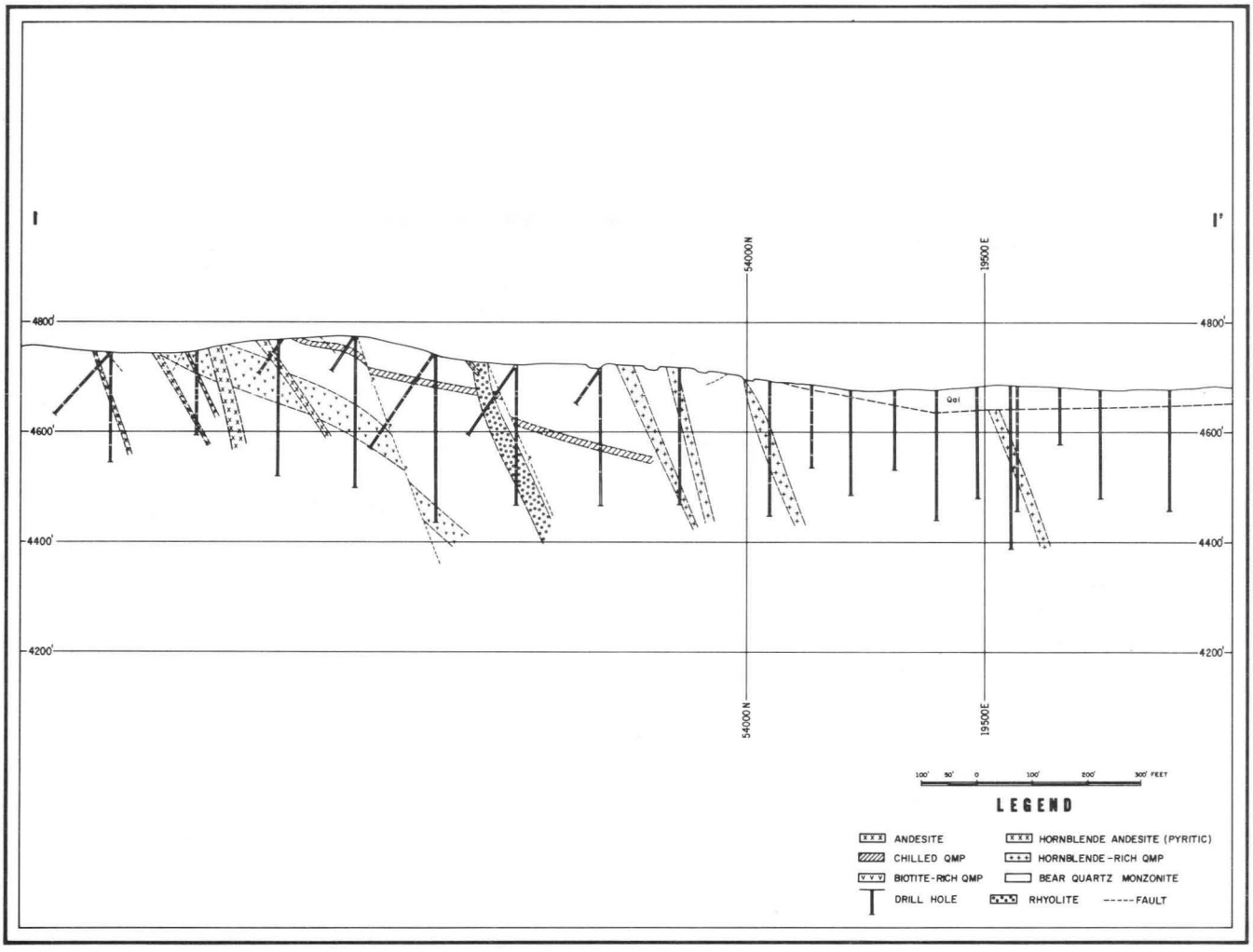

Fig. 5. Geologic cross section I-I', MacArthur oxide deposit

Areas containing +0.4% Cu form a crude east-northeast band across the well-defined northwest structural grain of the area. Figure 7 shows the +0.4% Cu grade blocks in relation to the southeast limit of the phyllic alteration zone. The individual grade blocks trend northwest and occur immediately east of the phyllic alteration zone. This alteration-grade relationship is interpreted to indicate that low-grade primary copper in the phyllic zone was dissolved by supergene solutions, transported and deposited as a copper oxide when it encountered the more reactive rocks with fresh feldspar. The addition of this exotic copper enriched the low-grade oxidized primary values to produce the areas of +0.4% Cu.

A leached zone immediately below the present bedrock surface was noted early in the trenching program. This zone ranges from zero to 10 feet in thickness and averages 1 or 2 feet. Within this superleach zone, no oxide copper values can be found. Drilling frequently penetrated a band of higher grade mineralization parallel to the bedrock surface as illustrated in Figure 8. This zone is interpreted to represent copper leached from the present bedrock surface and redeposited several feet below.

Andesite dikes with a high percentage of fresh calcic feldspar tend to "soak up" exotic copper. The dikes frequently contain over 1.0% Cu and are treated as veins in the ore-reserve calculations.

In several locations an area of higher copper grade was noted immediately above the top of sulfide (Fig. 8). A possible explanation for this higher grade would be oxidized chalcocite enrichment.

In summary, the MacArthur is an oxidized low-grade porphyry copper deposit which has been locally enriched by exotic copper. The probable source of the exotic copper was pri-

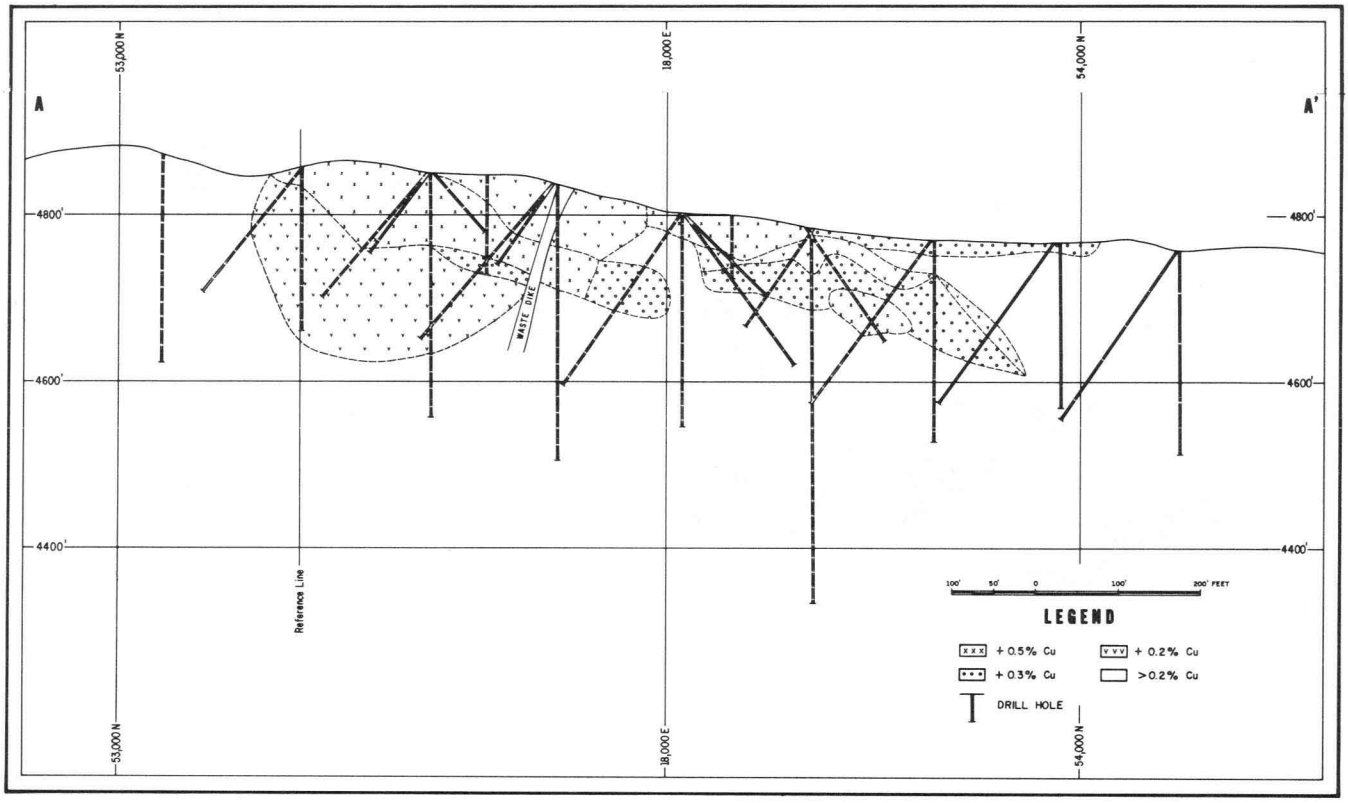

Fig. 6. Assay section A-A', MacArthur oxide deposit

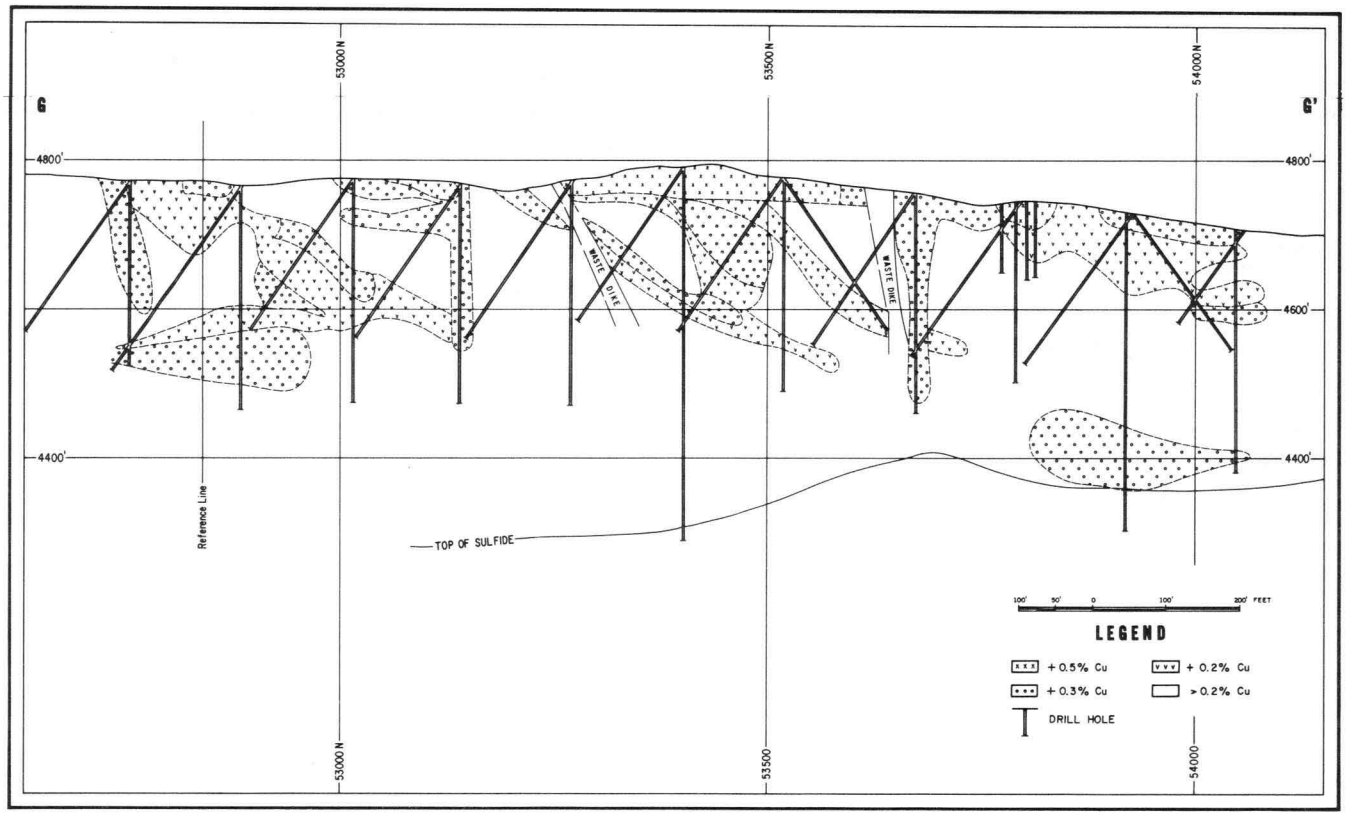

Fig. 7. Surface projection +0.4 percent copper grade, MacArthur oxide deposit

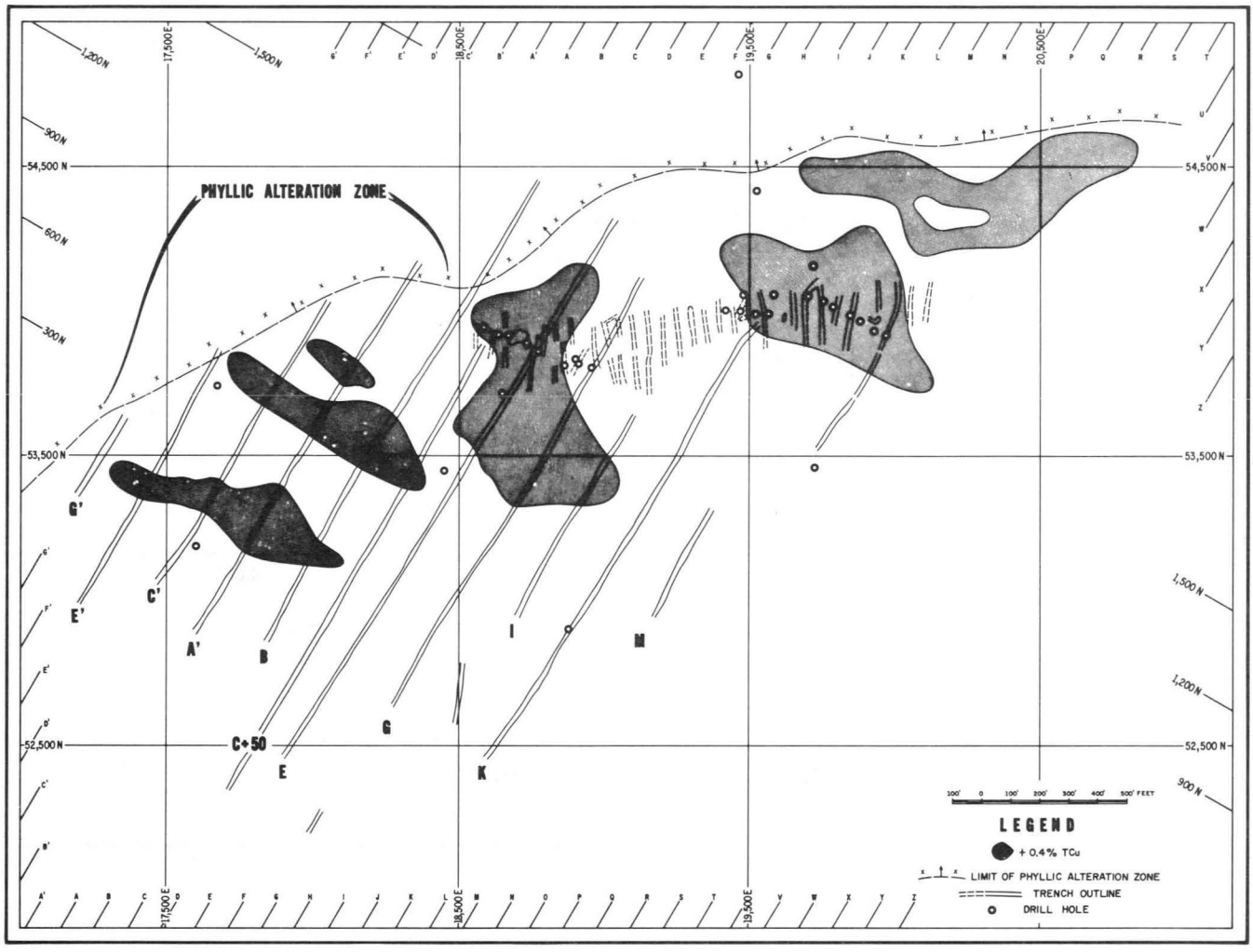

Fig. 8. Assay section G-G'

mary sulfide mineralization peripheral to the porphyry center.

Acknowledgments

I wish to thank the management of The Anaconda Company for permission to publish this paper. The illustrations were prepared by Mr. Andres Martin.

ALTERATION AND DISTRIBUTION OF SULFIDE MINERALIZATION AT COPPER CANYON, LANDER COUNTY, NEVADA

by

David W. Blake,[1] Ted G. Theodore,[2] and Edward L. Kretschmer[1]

Abstract

Hypogene sulfides, thermal metamorphic minerals, and hydrothermal alteration are related systematically to an altered granodiorite laccolith that intruded Paleozoic sedimentary rocks at Copper Canyon, Nevada, during the middle Tertiary. Associated with this granodiorite are two commercial Cu-Au-Ag porphyry deposits that formed exclusively in the adjacent wall rock. Total sulfide content in the granodiorite is generally less than 2 percent; uneconomic molybdenite mineralization occurs only in the granodiorite and its immediate wall rock. The granodiorite is surrounded asymmetrically by a widespread and very irregularly shaped high-sulfide shell in which the total sulfide content is greater than 2 percent; this asymmetry probably reflects both structural and chemical controls. All known Cu-Au-Ag orebodies are within the high-sulfide shell, and their economic boundaries are closely defined by rock having more than 1 volume percent pyrrhotite. The orebodies are for the most part in rock with the lowest iron-sulfide-chalcopyrite ratios determined for this porphyry system. In addition, two other high sulfide-low copper areas contain significant gold with minor silver.

Alteration effects at Copper Canyon reflect a combination of contact metamorphism and later hydrothermal alteration that have produced an irregular concentric pattern about the altered granodiorite. They are represented sequentially outward by potassic, phyllic, transitional, and propylitic zones. The potassic zone coincides with the Cu-Au-Ag mineralization and it includes the strong development of secondary biotite and K-feldspar.

Introduction

During the past several years many new and systematic descriptions of ore deposits have been published, including our studies at Copper Canyon, Nevada, that describe a small porphyry copper deposit containing significant concentrations of copper, silver, and gold. The bulk of these metals occur in the metamorphosed wall rock. This paper is a continuation of a cooperative study begun in 1968 by the U.S. Geological Survey and Duval Corporation to resolve some of the complex geologic relations associated with the Copper Canyon ore deposits and provide information that hopefully would aid in the exploration for similar types of metal occurrences.

Information for this paper has been taken from drill holes, detailed pit mapping, petrographic study of core and surface samples, and geologic examination of the immediate area. Several other papers thoroughly describe the geology and mineralization of the ore deposits and surrounding area. They include the earlier studies of Roberts (1964) and Roberts and Arnold (1965) that provided the necessary geologic framework on which our studies have been based, especially the regional structural and stratigraphic relations that greatly influenced the deposition of ore minerals. Later work by Sayers and others (1968), Nash and Theodore (1971), Theodore and others (1973), and Theodore and Blake (1975, 1977) described in detail the geology, geochemistry, and age of mineralization of the Copper Canyon deposits. These publications should be consulted for additional information.

[1] Duval Corporation, Battle Mountain, Nevada 89820

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Geology

General

The Copper Canyon deposits are located within the southern portion of the Battle Mountain mining district in north-central Nevada

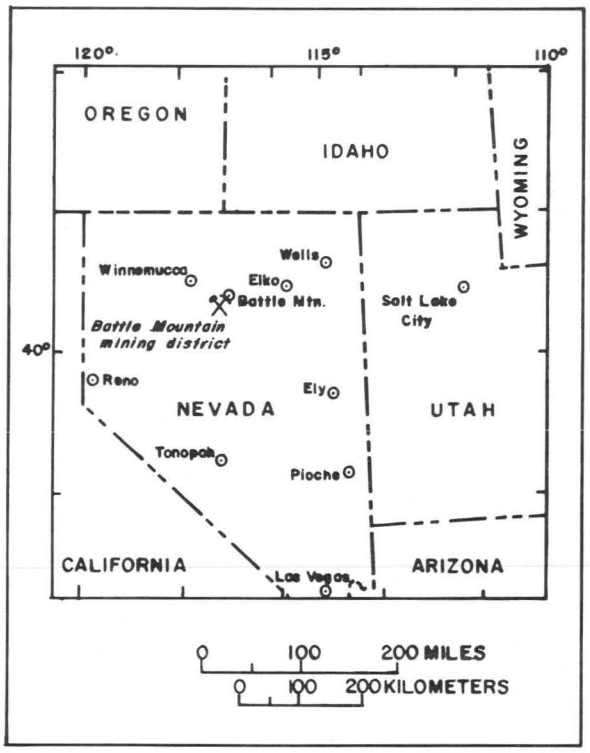

Fig. 1. Location map of the Battle Mountain mining district, Lander County, Nevada

about 15 miles south of Battle Mountain, Lander County, Nevada (Fig. 1). This mining district is located at the northern end of the northwest-trending Battle Mountain–Eureka mineral belt as delineated by mining districts and Tertiary intrusions (Roberts, 1966).

Figure 2 illustrates generally the stratigraphic and thrust relations that evolved during the Paleozoic and Mesozoic eras in the mining district. Three major thrust plates crop out within the Battle Mountain mining district:

1. The upper plate of the Roberts Mountains thrust, which is composed of chert, shale, argillite, greenstone, and quartzite of the Lower or Middle Cambrian Scott Canyon and Ordovician Valmy Formations.

2. These lower Paleozoic formations were overthrust by a block of clastic sedimentary rocks of the Upper Cambrian Harmony Formation along the Dewitt thrust, which moved sometime during the middle Paleozoic about the same time as the Roberts Mountains thrust (Roberts, 1964). An upper Paleozoic autochthonous sequence of rocks, the Antler sequence, rests unconformably on both the Valmy and Harmony Formations. The Antler sequence includes three formations: the Middle Pennsylvanian Battle Formation, the Upper Pennsylvanian and Lower Permian Antler Peak Limestone, and the Upper Permian Edna Mountain Formation. Rock types in these formations include conglomerate, limestone, and limy siltstone or shale.

3. Above the Antler sequence is the Golconda block, which is the uppermost thrust plate, which contains chert, argillite, and some limy siltstone of the Pennsylvanian and Permian Pumpernickel Formation and the Middle Pennsylvanian and Lower Permian Havallah Formation, which are composed of chert, sandstone, shale, and limestone.

Igneous activity in the Battle Mountain district occurred primarily during Cretaceous to middle Tertiary time (Theodore and others, 1973). These small plutonic stocks include the 87 m.y. granodiorite of Trenton Canyon and the late Eocene or early Oligocene (41-37 m.y.) granodiorite to quartz monzonite intrusions that occupy the northern and eastern portions of the quadrangle. Oligocene volcanic rocks within the district are represented by quartz latite, welded tuff, and pyroclastics belonging to the regionally extensive Caetano Tuff (McKee and Silberman, 1970). Some Tertiary basalt crops out along the south flank of Battle Mountain. The age of these flows is probably about 16 m.y. based on similar basalt flows that cap the Sheep Creek Range 30 miles north of Copper Canyon and dated by McKee and others (1971).

Geology of the Copper Canyon Area

Geology in the vicinity of the Copper Canyon pit is illustrated in Figure 3. Our discussion will focus on those units that have been metamorphosed and mineralized by the middle Tertiary granodiorite because of their control of the eventual distribution of alteration silicates and sulfides. Those Paleozoic formations that have been affected by metamorphism and mineralization within the contact aureole are the Scott Canyon, Harmony, Battle, and Pumpernickel. Two of these formations, the Battle and Pumpernickel, contain most of the economic concentrations of metals in the east and west orebodies, respectively.

Near the east edge of Figure 3, the Harmony and Scott Canyon Formations are bounded by the Plumas fault, one of several important north-south mineralized structures. East of the Plumas fault but still within the pyritic halo (Theodore and Blake, 1969), the Scott Canyon Formation is made up mostly of chert containing minor limestone and greenstone. Here the chert occurs as thin to medium-thick beds separated by shale partings (Roberts, 1964, p. A14), and it has a distinct dark gray to black color in contrast to that of the chert, which has been metamorphosed and mineralized. Metamorphosed and mineralized chert

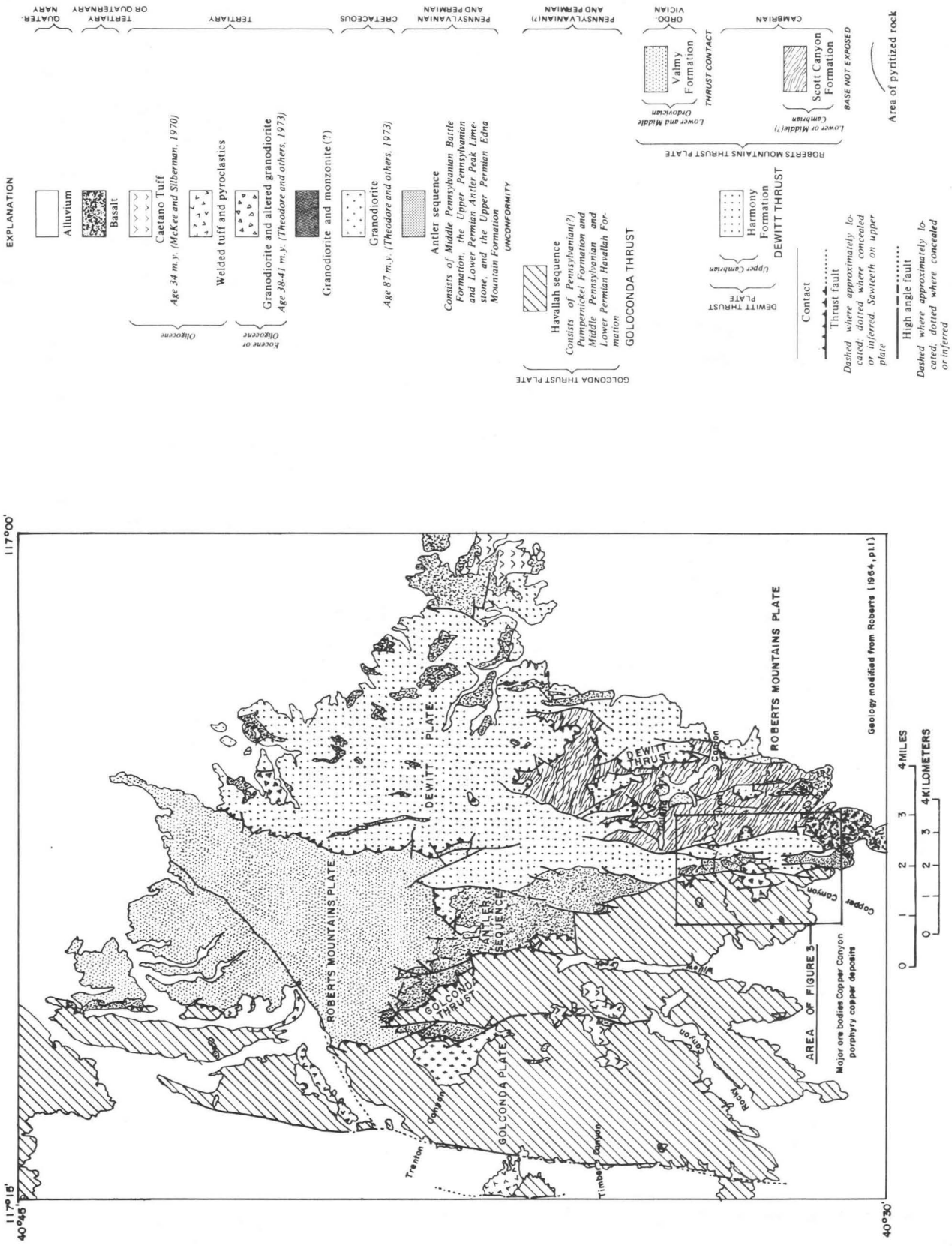

Fig. 2. Generalized geologic map of the Antler Peak quadrangle and Battle Mountain mining district, Lander County, Nevada

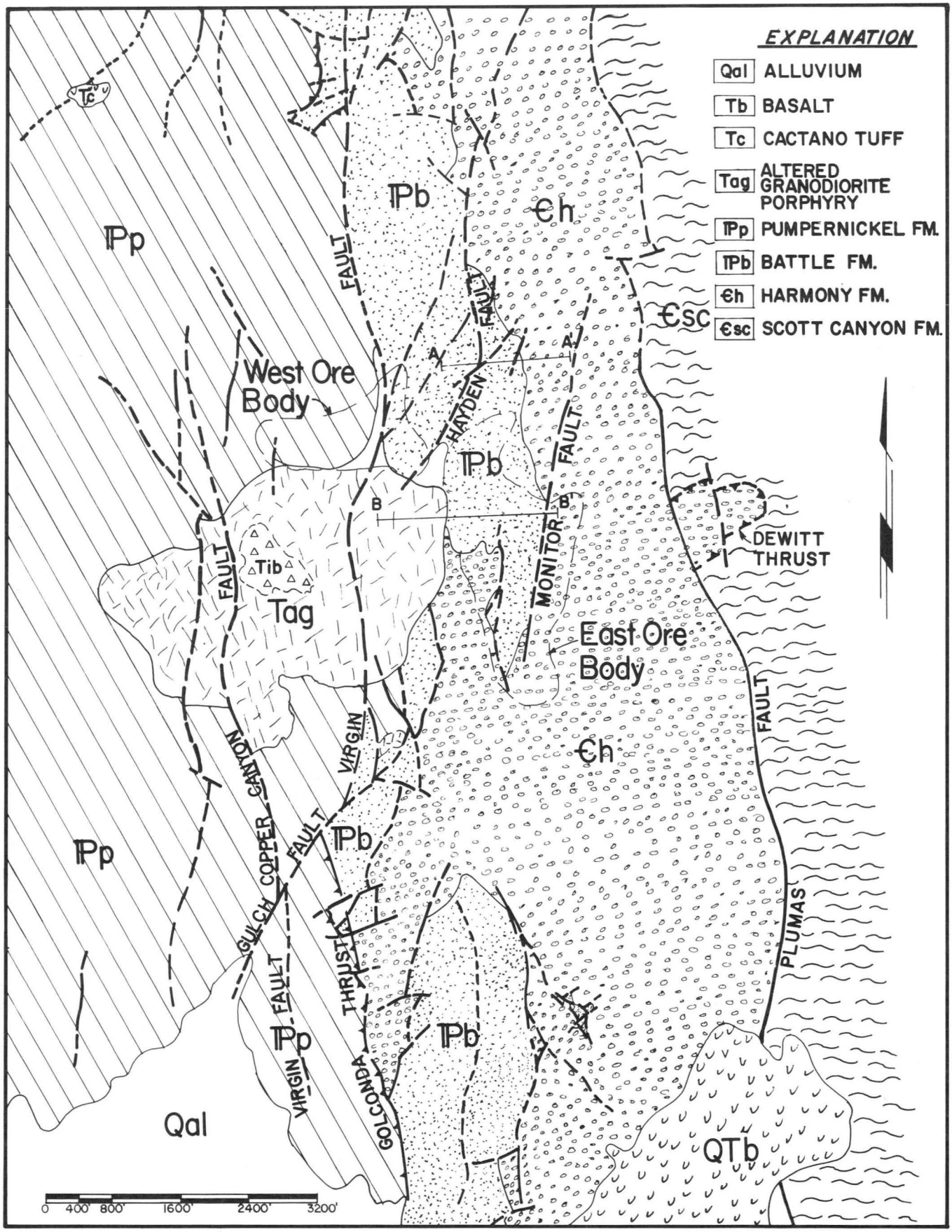

Fig. 3. Generalized geologic map of the Copper Canyon area, Lander County, Nevada

exhibits various degrees of recrystallization and is white and iron stained. Greenstone and limestone occur in the upper portion of the Scott Canyon Formation (Roberts, 1964, p. A15). The greenstone is locally overlain by limestone east of Figure 3. In all areas where limestone or greenstone crop out, they occur between chert. The limestone is blocky, light gray, and commonly pitted by solution cavities. Altered mafic andesite and basalt flows and pyroclastics compose the greenstone (Roberts, 1964, p. A15). Locally, along major faults and adjacent to small dikes or plugs of altered granodiorite, the greenstone has been metamorphosed to a biotite and tremolite assemblage containing pyrrhotite.

Underlying the Copper Canyon pit and cropping out to the east is the Harmony Formation. This formation consists of interbedded sandstone, siltstone, shale, and rare limestone, all of which have been metamorphosed and mineralized in the study area. Unaltered sandstone of the Harmony is composed of quartz, feldspar, biotite, and muscovite with variable amounts of clay minerals, quartz, and calcite as the cementing material, which locally can make up 20-30 percent of the rock (Roberts, 1964, p. A23-24). Where thermal metamorphism and hydrothermal alteration are intense, the sandstone has been converted to a biotite quartzite and the siltstone or shale to a dense biotite hornfels.

The most important host rock for ore mineralization at Copper Canyon is the Middle Pennsylvanian Battle Formation, which rests with a slight angular unconformity on the Harmony Formation. Total thickness of the Battle as determined from drill holes just north of the intrusion is 650 feet. This thickness for the Battle differs by about 100 feet from that of Roberts' (1964, p. A29) measured type section located about 3.5 miles north of the pit in the vicinity of Antler Peak and Cow Canyon. Here Roberts' total thickness for the Battle was 730 feet. The lower total thickness of the Battle in the mine area reflects a thinner lower member. All three members of the Battle, as described by Roberts, however, crop out in the mine area and include the lower calcareous conglomerate member, 250 feet thick; a middle member composed of calcareous shale, sandstone, and a very minor amount of conglomerate 100 feet thick; and the upper member of siliceous conglomerate, 300 feet thick.

The conglomerates consist of subangular to subrounded quartzite, chert, and few limestone clasts locally set in a limy matrix. In the areas affected by metamorphism and hydrothermal alteration the former limy matrix of the calcareous conglomerate has been metamorphosed predominantly to a tremolite and quartz assemblage containing minor amounts of biotite and diopside. Although similar clasts occur in the siliceous conglomerate, the matrix instead consists of recrystallized fine- to medium-grained quartzitic sandstone, which is commonly biotitic. Within the contact aureole, the middle member is altered to a calc-silicate hornfels and locally skarn composed of various amounts of tremolite, quartz, biotite, diopside, and garnet. Metamorphism of calcareous sedimentary rocks of the Battle and Pumpernickel Formations produced the calc-silicate and skarn bodies that greatly influenced the later subsequent deposition of hydrothermal sulfides.

The two major members of the Pumpernickel Formation adjacent to and west of the Copper Canyon mine have been described in detail by Theodore and Blake (1975, 1977). A lower argillite member contains interbedded chert, siltstone, and minor sandstone and calcareous argillite, and the overlying chert member consists predominantly of chert and shale partings. Calcareous argillite of the lower argillite unit of the Pumpernickel is 50 to 150 feet thick and occurs immediately on the upper plate of the Golconda thrust north and south of the Copper Canyon intrusion. Nowhere was this calcareous argillite unit exposed prior to 1976 and all information before then was gathered from drill holes (Theodore and Blake, 1975, 1977). In 1976, mining of the west orebody has exposed the calc-silicate and garnetite orebody. Metamorphism of the calcareous argillite has produced a tremolite and diopside envelope about a garnet-rich skarn. Later hydrothermal solutions have deposited pyrite, pyrrhotite, and chalcopyrite within the metamorphosed assemblage that contains significant concentrations of gold and silver. The genetic implications and petrogenesis of the garnetized unit are discussed by Theodore and Blake (1975, 1977).

All of these Paleozoic sedimentary rocks have been intruded by a nearly equidimensional, 3,500-foot-wide granodiorite laccolith (Theodore and others, 1973; Theodore and Blake, 1975). This altered granodiorite consists of phenocrysts of biotite, plagioclase, hornblende, and quartz set in a groundmass of very fine grained biotite, quartz, and K-feldspar with accessory apatite, zircon, allanite, rutile, and traces of magnetite (Theodore and Blake, 1975). Secondary copper is very prominent in many surface exposures of altered granodiorite, especially adjacent to the east orebody where the secondary copper has replaced altered plagioclase phenocrysts (Clement, 1968).

Significant ore-bearing north-south structures include, from east to west, the Plumas,

Monitor, Hayden, Virgin, and Copper Canyon faults (Fig. 3). These high-angle normal faults, which dip westerly and have separations from 100 to in excess of 750 feet, channeled the flow of metal-bearing fluids. The Virgin fault has also controlled the intrusion of the granodiorite porphyry. South of the intrusion, the Golconda thrust is exposed and generally dips at low angles westward. Although it has been suggested previously that this thrust had localized the ore-forming fluids, drill-hole data indicate that the thrust did not impound such fluids, but more importantly it placed in juxtaposition the favorable rock types that allowed the development of a significant contact metamorphic ore occurrence.

Sulfide mineralization in the Copper Canyon deposits is reflected by pyrrhotite, pyrite, chalcopyrite, chalcocite, covellite, and lesser quantities of arsenopyrite, sphalerite, galena, marcasite, and molybdenite, which occur as disseminations, fracture filling, quartz veinlets, veining, and replacements. These sulfides are concentrated into two orebodies, the east and west (Sayers and others, 1968) as outlined in Figure 3. Presently (1976) the west orebody is being developed and mined and the east orebody has been depleted of ore. Metallization in the east orebody has been confined chiefly to the lower 50-75 feet of the lower member of the Battle Formation. In the west orebody ore values are found in the calc-silicate hornfels and skarn bodies of the Pumpernickel Formation.

Distribution of Sulfide Minerals

To describe the distribution of sulfides at Copper Canyon we have prepared four figures to illustrate their overall relations to the altered granodiorite porphyry and wall rock. These minerals include molybdenite, pyrrhotite, pyrite, and chalcopyrite with the latter two combined with pyrrhotite to show the total sulfide content and the ratio of iron sulfide to chalcopyrite.

As shown in Figure 4, molybdenite is restricted to the Copper Canyon intrusion and the immediate wall rock. The area outlined in Figure 4 contains Mo assay values ranging from 0.005% to a high of 0.02%. Here molybdenite is commonly associated with pyrite, chalcopyrite, and pyrrhotite assemblages together with gangue minerals K-feldspar and quartz as veinlets in the altered granodiorite porphyry, metasandstone, and metashale of the Harmony and the metaconglomerate of the Battle. Most molybdenite was deposited during an early phase of hydrothermal activity (Theodore and Blake, 1975, Fig. 35, p. B41,

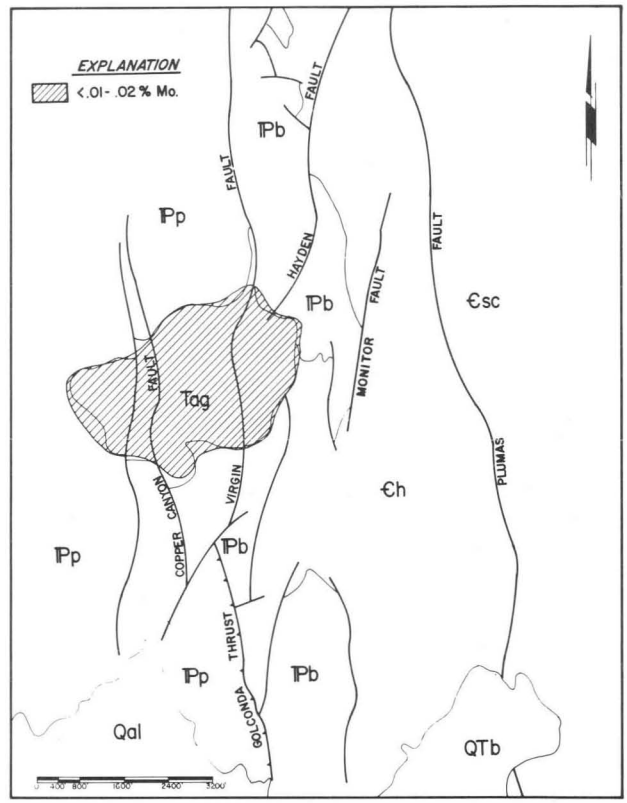

Fig. 4. Distribution of molybdenite, Copper Canyon, Lander County, Nevada

and Roberts and Arnold, 1965, Fig. 7, p. B25) and occurs within the potassic alteration zone. Geochemical sampling by Theodore (1969, Fig. 15) showed a greater than 15 ppm Mo concentration over the intrusive body at Copper Canyon.

Although pyrrhotite is an uncommon sulfide mineral in the porphyry copper deposits of the southwestern United States, it is a rather common hypogene mineral associated with economic mineralization in the Battle Mountain mining district. Pyrrhotite occurs in the sedimentary rocks as well as the mineralized igneous rock. This mineral is common in many mineralized areas throughout the northern part of Nevada. Pit mapping within the Copper Canyon deposit and drill-hole data show that pyrrhotite is concentrated at greater than 2 volume percent in two separate areas north of the intrusion (Fig. 5). The western high reflects the Pumpernickel skarn unit, which locally contains up to 25 percent pyrrhotite, and the eastern high reflects pyrrhotite in the basal member of the Battle Formation directly above the Harmony Formation. In both of these areas, pyrrhotite occurs as a disseminated sulfide replacing favorable beds.

Forming an arcuate pattern around nearly

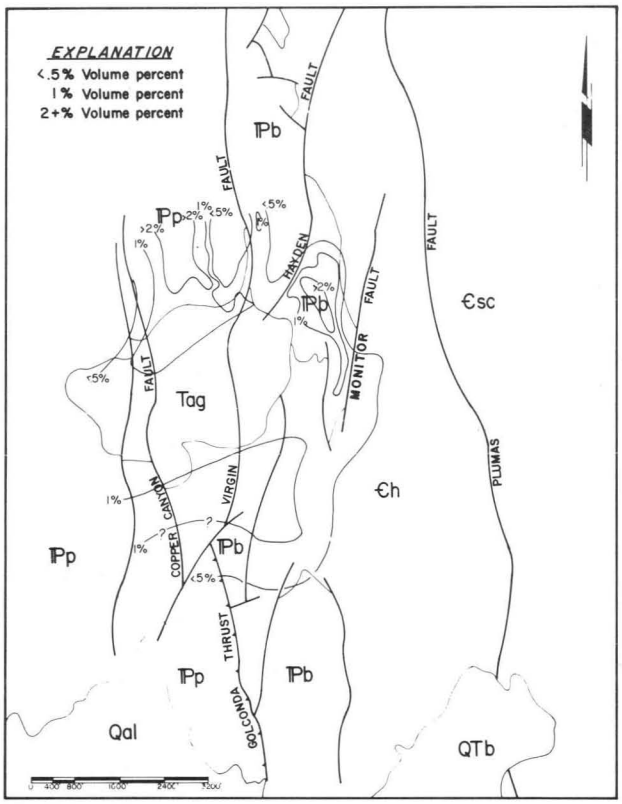

Fig. 5. Distribution of pyrrhotite (estimated volume percent), Copper Canyon, Lander County, Nevada

three-quarters of the altered granodiorite is an irregularly shaped volume of rock where pyrrhotite is greater than one volume percent in the wall rocks. Within the intrusion, however, the pyrrhotite content is less than 1 but more than 5 percent, as shown in Figure 5. Outward from the intrusion, the outer limits of pyrrhotite mineralization are represented by the less than 0.5% line, which uniquely demonstrates a zonal pattern. This outer limit is not known precisely because of the lack of drill holes and the difficulty of recognizing pyrrhotite in its oxidized form. Overall, the distribution of this mineral is spatially associated with the intrusive body at Copper Canyon. Elsewhere in the district similar relationships have been observed between igneous intrusions and host sedimentary wall rocks.

Most of the pyrrhotite occurs as replacement beds or mantos, disseminations in the calc-silicate–skarn unit of the Pumpernickel, and as disseminations in the lower part of the Battle conglomerate. Also pyrrhotite is disseminated in metasandstone of the Harmony. Veinlets of pyrrhotite with chalcopyrite, K-feldspar, and biotite occur in both the Harmony and Battle Formations. In the altered granodiorite porphyry, pyrrhotite is found in K-feldspar and quartz veinlets as well as disseminated in the groundmass (Theodore and Blake, 1975).

The distribution of total volume sulfides, including pyrite, pyrrhotite, chalcopyrite, and marcasite, is shown in Figure 6 as determined from drill-hole information. The greater than 4 percent contour reflects the skarn mineralization at the west orebody and the total content in the Battle Formation north of the intrusion. South of the altered porphyry, the 4 percent plus contour is associated with a high pyrite-gold area at the base of a block of lower member Battle conglomerate. The interval 2-4% sulfide forms a high sulfide shell peripheral to the Copper Canyon intrusion and within the host metasedimentary mineralized rocks. Although this pattern appears to be more widespread south of the intrusion in the vicinity of the old Copper Canyon underground mine, the data here are very limited because of sparse drill-hole information. Most of the economical mineralization, including that in the area south of the intrusion, is concentrated within the high-sulfide shell.

The total sulfide content of the altered granodiorite is less than 2 volume percent and averages about 1.65 percent. This low over the intrusion and the high-sulfide shell illus-

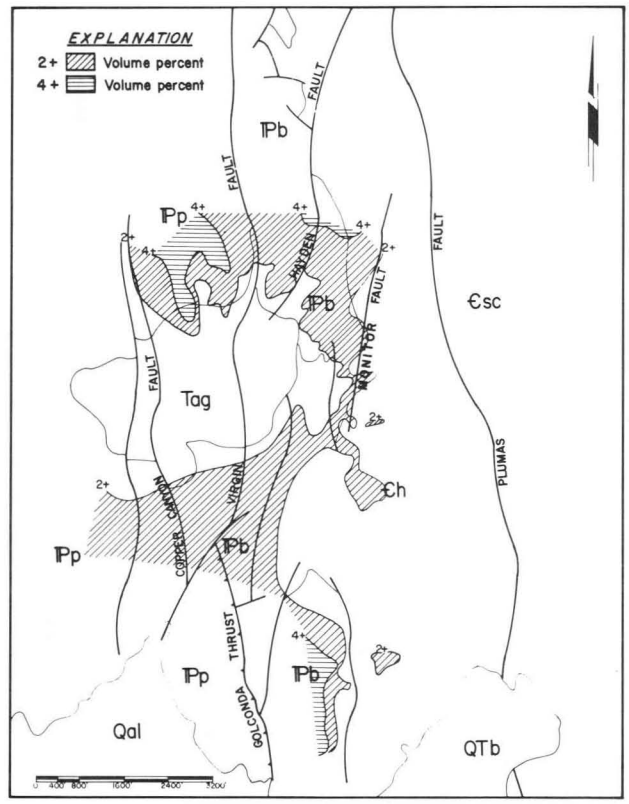

Fig. 6. Distribution of total sulfide content, Copper Canyon, Lander County, Nevada

trate the close zonal relationship of the granodiorite with mineralization and the association of a higher sulfide interval with the wall rock, which contains the economical mineralization.

To appreciate and understand more fully the relationship and correlation of sulfide mineralization associated with the ore deposits at Copper Canyon, we have contoured the ratio of iron sulfide to chalcopyrite (Fig. 7). In computing these ratios, iron sulfide represents the total pyrite, pyrrhotite, and marcasite, if present, and is contoured in the following intervals: 0-5, 6-10, 11-15, 16-20, and > 20 to 1.

The lowest iron sulfide-chalcopyrite ratio occurs where the economic Cu-Au-Ag mineralization was found in the rocks of the Pumpernickel skarn and calc-silicate, lower member of the Battle, and the Harmony Formation and coincides with the east and west orebodies (Fig. 3). This low iron sulfide–chalcopyrite zone is within the high-sulfide shell and has an average ratio of 4 to 1. In the intrusion, the iron sulfide–chalcopyrite ratio averages 7 to 1.

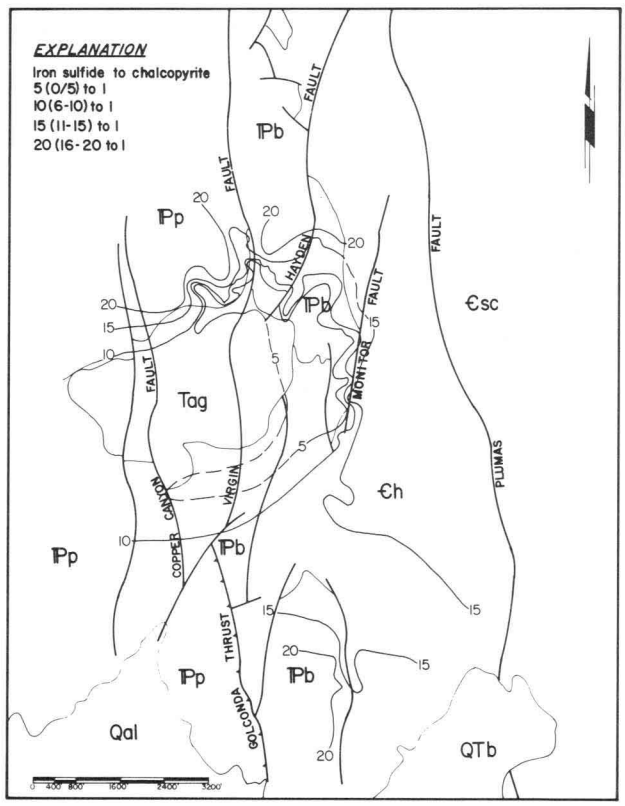

Fig. 7. Distribution of iron sulfide–chalcopyrite ratios, Copper Canyon, Lander County, Nevada

Three areas of greater than 20 to 1 iron sulfide to chalcopyrite are shown on Figure 7. The area directly north of the intrusion is related to the high content of pyrite and pyrrhotite in the Pumpernickel skarn and calc-silicate unit with a substantial decrease in chalcopyrite. Drill-hole information depicts the relationship of chalcopyrite adjacent to the intrusion and its decrease outward. In the other two areas, north-northeast and south of the altered granodiorite, pyrite and minor pyrrhotite mineralization is abundant but with very low overall content of chalcopyrite. A significant amount of gold and some silver in the lower Battle conglomerate in these two areas reflects the gradual outward decrease of copper sulfide and a corresponding increase of gold together with the high pyrite content.

Structural relations that have influenced the distribution of the iron sulfide–chalcopyrite ratios are also locally important. This is best illustrated in the vicinity of the Virgin and Hayden faults north of the intrusion (Fig. 3), both of which are normal north-south-striking faults. In both instances, the lower iron sulfide–chalcopyrite ratios occur in the footwalls and the higher ratios occur in the hanging walls. For the Hayden fault the distribution of these ratios is not directly related to rock types because both walls are Battle. Previous studies have shown the importance of the mineralized faults on the control of fluids during ore deposition (Theodore and Blake, 1975).

Alteration

As outlined earlier in the paper, numerous data have been collected to study the alteration types and products associated with the Copper Canyon deposits. Equally significant is the fact that two distinct but closely related periods of metamorphism and thermal and hydrothermal alteration have affected the Paleozoic sedimentary rocks. These combined thermal alteration phenomena at this porphyry copper deposit allowed us to relate paragenetically the salient economically important features of hydrothermal alteration in such a deposit. Alteration types used in this paper are based on the classifications of Creasey (1966) and Lowell and Guilbert (1970). A future paper is planned that will more fully describe the hydrothermal alteration at Copper Canyon using data from recent drill holes south of the Copper Canyon intrusion.

The potassic zone covers an area approximately three quarters of a square mile centered over the altered granodiorite and immediate wall rock (Fig. 8). An average width of

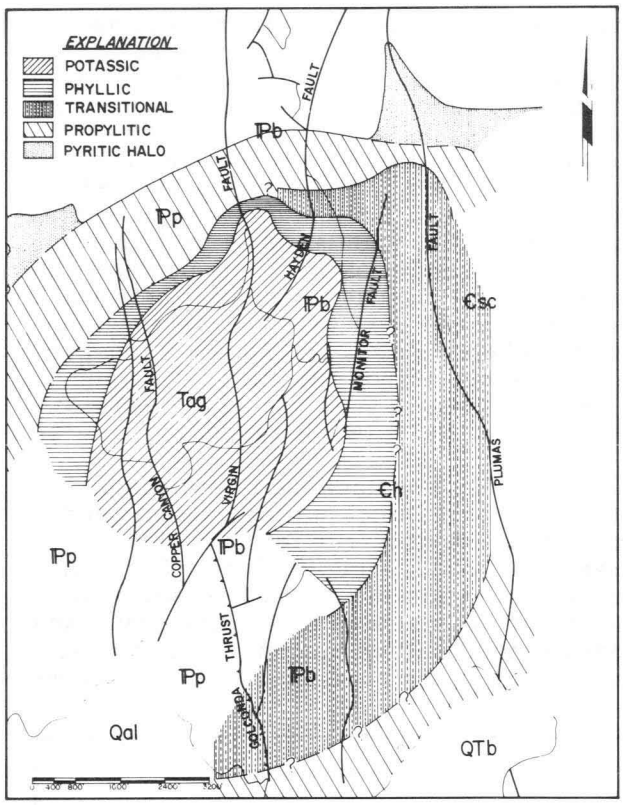

Fig. 8. Alteration zones at Copper Canyon, Lander County, Nevada

this zone from the edge of the intrusion outward is about 1,000 feet. Silicate minerals of the potassic zone are primarily biotite and K-feldspar where they occur as replacements or in veins along with quartz. Potassic alteration of the altered granodiorite in the more intensely altered zones is represented by primary igneous biotite and hornblende, which have recrystallized to an intergrowth of fine-grained secondary biotite. Phenocrysts of plagioclase are rimmed and partially replaced by K-feldspar. The hydrothermal groundmass of the porphyry consists of a mosaic of quartz, K-feldspar, and local biotite, which is complexly intergrown and has sutured boundaries (Theodore and Blake, 1975). Potassic alteration effects in the matrix of the Harmony and Battle Formations consist of quartz, K-feldspar, and biotite that contain intergrown sulfide minerals.

Chert and argillite of the Pumpernickel Formation adjacent to the Copper Canyon intrusion that has been potassically altered is recrystallized to a sugary quartzitic-textured rock containing intergrown anhedral quartz and K-feldspar. Although the hydrothermal effects on the chert can be recognized in the field, its recrystallization to a fine-grained quartzitelike rock does make positive identification uncertain unless outcrops of less altered chert can be found outside the limits of mineralization. Fibrous biotite is also present in potassic altered chert (Roberts and Arnold, 1965, p. B13). Secondary biotite and K-feldspar occur in the argillite of the Pumpernickel Formation and both of these alteration minerals replace and vein the calc-silicate unit of the west orebody (Theodore and Blake, 1977).

The phyllic zone, as shown in Figure 8, depicts a narrow irregular pattern outside the potassic zone, and it is recognized by the occurrence of sericite combined with silicification. The width of this zone ranges from about 300 to 1,600 feet and averages 1,000 feet. Based on this preliminary study, sericite occurs as replacement of primary feldspars and groundmass or matrix of igneous and sedimentary rocks, respectively. In the metasandstones, sericite is also an important alteration product of the former clayey matrix, and in both shales and sandstones, it has formed as a recrystallization product of detrital grains of muscovite. Cherts of the Pumpernickel exhibit an increase in the size of the quartz grains, which have sutured borders. The shaly material has been recrystallized to sericite (Roberts and Arnold, 1965, p. B13). Quartz veinlets with sericite selvages are prevalent in the phyllic alteration zone. As shown in Figure 8 this zone is not well documented to the south beyond the porphyry contact because of the lack of detailed information. In the northern portion of the study area, including the Virgin and Hayden faults, well-developed silicification with sericite and clay minerals has pervasively altered the walls of these major faults, even locally where they transect the potassic zone.

Because of the variable rock types and nondefining hydrothermal alteration products, combined with thermal metamorphism, we have decided to describe the alteration in the next zone outward as transitional, a type lying between potassic-phyllic and propylitic. Within this transitional zone there are no well-defined alteration assemblages that would belong to any of the classic porphyry zones. During this preliminary study, we observed the effects of both hydrothermal and contact metamorphic phenomena in the transitional zone. The transitional type, as illustrated in Figure 8, occurs primarily in the eastern half of the area and forms a fairly broad envelope outward from the granodiorite and the phyllic zone. Geologically, this area includes the Battle and Harmony Formations and a small part of the Scott Canyon. Its eastern continuation is unknown. Where this zone has been mapped it has a uniform width of about 2,000 feet.

Mineralogy of this zone is represented by the recrystallization assemblages of biotite, tremolite, and quartz that most likely accompany contact metamorphism. Also, most likely associated with the contact event is the recrystallization of some sericite and other clay minerals and the development of tremolite-bearing hornfels from calcareous sedimentary rocks. Superposed hydrothermal minerals include the introduction of additional tremolite in veins, quartz, and local quartz–K-feldspar veinlets. These quartz-tremolite veinlets commonly crosscut the earlier contact metamorphism. The intensely recrystallized fabric that is very pronounced in the potassic zone is not as well developed in the transitional zone. Associated with the hydrothermal alteration is the recrystallization of biotite and muscovite and weak silica augmentation of detrital quartz grains.

Propylitic and potassic are the most recognizable alteration types in the Copper Canyon area. The outer boundary of the propylitic zone nearly parallels that of the pyritic halo and its outer limits have not been shown in Figure 8. Because of structural control of ore fluids and related igneous dikes and small stocks, the propylitic alteration zone extends westward and to the south for several thousand feet. More than likely some of the development of typical propylitic alteration assemblages may be the result of thermal metamorphism, but their distribution does indicate the outer limits of mineralization and alteration associated with the Copper Canyon intrusion. Minerals recognized in this alteration zone include chlorite, epidote, quartz, clays, sulfides, tremolite, and calcite. Propylitic alteration of igneous rocks produced epidote and calcite replacing the plagioclase feldspar and chlorite replacing the mafic minerals biotite and hornblende. The matrix of sandstone has been replaced by montmorillonite, chlorite, and calcite. Detrital biotite is altered or partially altered to chlorite. In the Battle Formation, chlorite, clays, tremolite, and epidote occur as replacement products of the calcareous matrix. Various alteration products occur as veins and veinlets in all rocks and include sulfide + tremolite + clay, quartz + epidote, quartz + calcite, and sulfide + clay + chlorite.

Summary

All present-day mining activity at Copper Canyon has concentrated on the Cu-Au-Ag metals within the east and west orebodies. This paper has demonstrated that these metals occur within the potassic alteration zone, the 2-4 percent total sulfide zone and in areas where there is a low iron sulfide–chalcopyrite ratio. Equally as important is the occurrence of gold peripheral to the base and precious metal association at Copper Canyon. These relationships are shown diagrammatically as cross sections in Figure 9 through both the Cu-Au-Ag and the Au-Ag metal occurrences. Section A-A' (Figs. 3 and 9) is about 1,600 feet north-northeast of the altered granodiorite and represents Au with minor Ag metallization in the lower member of the Battle conglomerate. Section B-B' is through the contact between the intrusion and the Battle and Harmony Formations where Cu, Au, and Ag occur together. Each metal occurrence illustrates differences in total sulfide content, iron sulfide–chalcopyrite ratios, and alteration types.

Figure 10 summarizes the relationship of alteration zones, total sulfide content, and iron sulfide–chalcopyrite ratios for two different metal occurrences at Copper Canyon. The Cu-Au-Ag mineralization is associated with a low iron sulfide–chalcopyrite ratio and moderate total sulfide content and is almost entirely within the potassic zone. The occur-

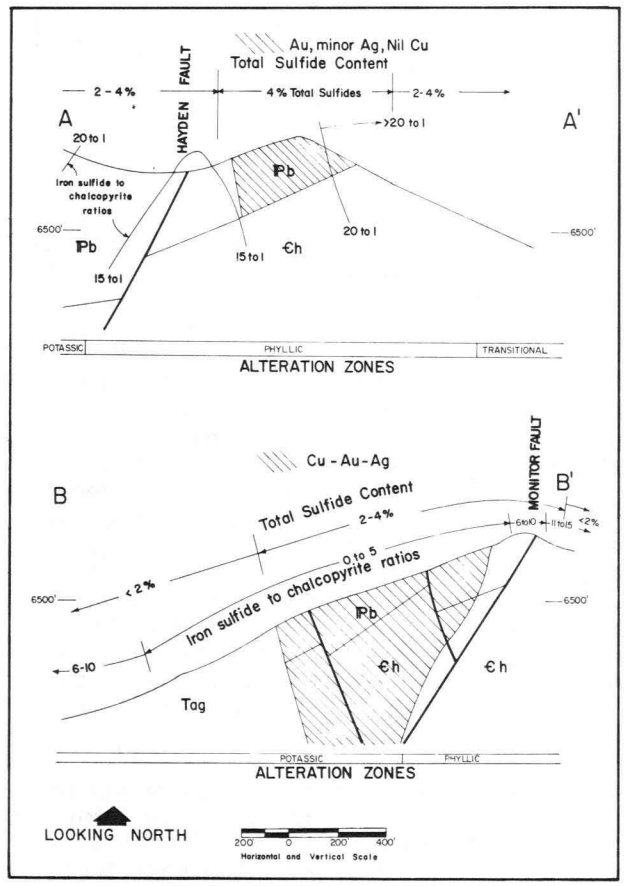

Fig. 9. Generalized east-west cross sections showing the relationship between mineralization and alteration, Copper Canyon, Lander County, Nevada

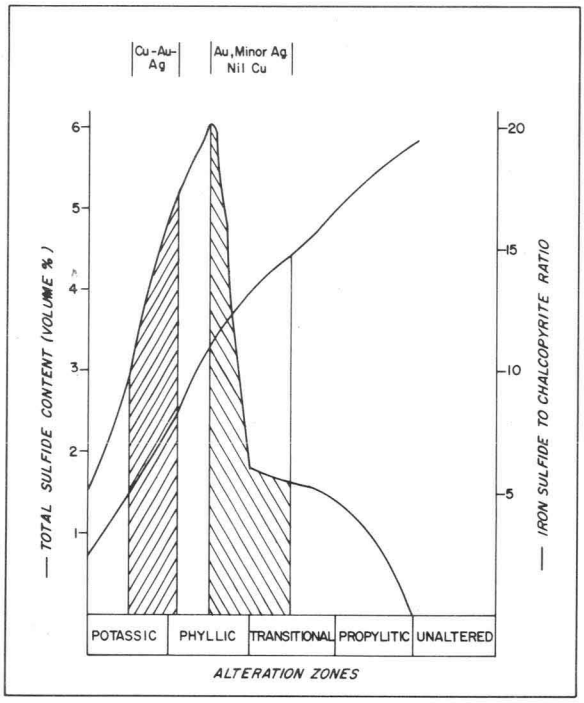

Fig. 10. Relationship of alteration types to total sulfide content and iron sulfide–chalcopyrite ratio, Copper Canyon, Lander County, Nevada

rence of gold with minor silver and no copper forms a broad zone of high to low total sulfide content and an increasing iron sulfide–chalcopyrite ratio. This gold metallization spans the boundary between the phyllic and transitional alteration zones.

Results of this study combined with previous work attempt to relate the combined effects of thermal metamorphism, hydrothermal alteration, and mineralization as found at the Copper Canyon deposits. These studies have shown that the mineralization process here is a continuous one that evolved from the thermal metamorphism stages to the final development of an ore deposit. The overlapping hydrothermal alteration and mineralization on earlier thermal metamorphism and skarn development are a geological process that culminated in the development of an economically important base and precious metal occurrence in the contact aureole of the mid-Tertiary Copper Canyon intrusion.

Acknowledgment

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RECENT GEOLOGICAL DEVELOPMENTS AT THE BAGDAD PORPHYRY COPPER DEPOSITS, EUREKA MINING DISTRICT, YAVAPAI COUNTY, ARIZONA

by

Purnendu K. Medhi [1]

Abstract

Cyprus Bagdad Copper Company and its predecessor companies have been operating at the Bagdad porphyry copper deposit for the last four decades. Mining and milling capacity of the present operation is 6,000 tons per day, and the deposit is now being prepared for production at a mining and milling rate of 40,000 tons per day. The expanded operation is scheduled to go on stream by December 1977.

The regional geology is characterized by a section of metamorphosed sediments which is intruded by felsic to basic intrusive rocks of Precambrian age. This Precambrian metamorphosed and igneous complex was intruded by a series of stocks, plugs, and dikes during the Laramide age. These intrusive bodies form a seven-mile-long belt along a N. 60°-70° E. trend. At present, the Bagdad stock is the largest and only productive intrusive body in this belt.

The Bagdad stock, which hosts copper-molybdenite mineralization, is a granodiorite-monzonite-quartz monzonite porphyry intrusion. Within this single major intrusive unit, separate intrusive rock units are recognized, although chemical, mineralogical, and age relationships are not completely known.

Hypogene sulfides consist of chalcopyrite and pyrite with a minor amount of molybdenite, which occur primarily in veinlets and microveinlets and, to a lesser degree, are disseminated in zones of pervasive alteration. A close relationship exists between certain silicate mineral assemblages and hypogene sulfide minerals.

Four major types of silicate alteration assemblages are biotite-albite-orthoclase-quartz-sericite, biotite-orthoclase-quartz-sericite, quartz-sericite-clay, and clay-chlorite-quartz-sericite. These silicate mineral assemblage zones are in part overlapping, vertically as well as laterally.

From the present data, it is hard to speculate on the pattern of concentric zoning of alteration, as typically observed in some porphyry copper deposits of the world. However, the Bagdad porphyry copper deposit exhibits certain similarities in regard to alteration and mineralization to most of the porphyry copper deposits of the southwestern United States.

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THE ROOT-ZONE CHARACTERISTICS OF PORPHYRY COPPER DEPOSITS

by

W. P. Durning[1] and J. D. Davis[2]

Abstract

The root-zone characteristics of porphyry copper systems and their recognition is of considerable importance to the exploration geologist. Deep-level and root-zone alteration and mineralization features described by previous authors at San Manuel–Kalamazoo, Arizona; the Fortuna pluton and Los Loros, Chile; the Appalachian porphyry systems and the Cornelia pluton, Arizona, are summarized.

The Little Hill Mine area located 25 miles north-northwest of Tucson, Arizona is described in detail and is interpreted to be the exposed root zone of a porphyry copper system. The upper level, and potentially economic portion of this porphyry copper system, has been removed by erosion or faulting. The rocks at Little Hill are principally Precambrian schist and quartz monzonite intruded by a Laramide(?) quartz monzonite stock and postmineral dikes. The west-northwest-trending, south-dipping Mogul fault is the principal structure in the area. Alteration and mineralization at Little Hill cover an area approximately 8,000 x 4,500 feet. The alteration and mineralization can be divided into three zones: the inner, middle, and outer. These zones are defined by specific alteration suites which roughly correspond to copper grade and pyrite-chalcopyrite ratios. The alteration-mineralization zones form a nonconcentric pattern elongated along the Mogul fault and truncated by it to the south.

The geologic, alteration, and mineralization features identified at Little Hill when compared with well-known porphyry copper deposits suggest it is the root-zone of a porphyry copper system.

The importance of recognizing root-zone features at an early stage in an exploration program is discussed. A table is presented which outlines many of the features that characterize porphyry copper root zones and compares them with similar features of hood zones with which they are often confused.

Introduction

Identification of the root-zone characteristics of porphyry copper deposits is of considerable importance to mineral exploration programs. The attributes of such deep-level alteration and mineralization have received little published attention, have remained inadequately characterized, and may be confused with hood-zone characteristics. A quote from Peter Joralemon (1975, p. 33) illustrates the problem. "The study of depth and mineralogic zoning as a tool for ore finding is perhaps also overvalued. I know of a possible porphyry copper occurrence that was turned down by two able geologists: one because erosion had clearly stripped the deposit down to its very roots, and the other, seeing the same evidence, because the ore body was still buried at a depth of over 5000 feet below the surface."

This paper presents the results of a detailed geological, geophysical, geochemical, and petrographic study of the Little Hill Mine area, Arizona. Particular attention is given to identifying those characteristics of deep-level alteration and mineralization in porphyry copper deposits that distinguish root-zone from hood-zone propylitization. The results are then discussed with respect to their application in mineral exploration programs.

Previous Studies

Articles by Lowell (1968), Lowell and Guilbert (1970), Sillitoe (1973), Hollister, Potter, and Barker (1974), and Wadsworth (1968) make

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note of deep-level alteration and mineralization in the context of broader discussions.

San Manuel–Kalamazoo Orebody, Arizona

Lowell (1968) and Lowell and Guilbert (1970) tentatively identified a deep-level alteration and mineralization assemblage in the Kalamazoo portion of the San Manuel–Kalamazoo orebody, Arizona. The outer portions of this deep-level zone are characterized by slight augmentation of quartz; minor alteration of K-feldspar to sericite; saussuritization of plagioclase by sericite, chlorite, and epidote; alteration of ferromagnesian silicate minerals to chlorite, epidote, carbonate, and magnetite; and by the augmentation of magnetite. The inner portions of this deep-level zone are transitional to a potassic alteration assemblage, as indicated by the appearance of secondary K-feldspar and biotite and by the pyritization of magnetite. Deep-level sulfide mineralization is characterized by Lowell (1968) as being bleblike, with a high ratio of chalcopyrite to pyrite but with overall low copper values owing to the low total sulfide content.

Fortuna Pluton, Chile

Sillitoe (1973) suggests that the Fortuna granodiorite may be an upthrown, deep-level portion of the Chuquicamata porphyry copper system. The granodiorite contains pegmatitic areas and a stockwork of copper oxides. Alteration in the Fortuna granodiorite is weak, and the rock becomes less porphyritic and more equigranular with depth.

Los Loros, Chile

Mineralization and alteration at Los Loros, Chile are described by Sillitoe (1973) as characteristic of a deeply eroded porphyry copper system within a large, equigranular, granite pluton. A central core of potassically altered rock changes laterally into propylitically altered rock, then into fresh granite. Deep-level potassic alteration consists of late magmatic to deuteric quartz, K-feldspar, sericite after plagioclase, and chlorite after primary biotite, with minor calcite and secondary biotite. Pyrite and secondary magnetite are the most conspicuous metallic minerals, and only minor amounts of chalcopyrite and molybdenite are present.

Appalachian Porphyry Systems

Hollister and others (1974) discuss porphyry mineral deposits of the Appalachian orogen. These mineral deposits are much older (346-580 m.y.) than the southwestern porphyries and have apparently been eroded to a much deeper level.

Appalachian porphyry mineralization is associated with equigranular to porphyritic quartz monzonite intrusions. The cores of these intrusions may locally contain small amounts of disseminated pyrite, chalcopyrite, bornite, and molybdenite, but more commonly they are fresh and unmineralized. Enveloping this central core are concentric alteration zones: (1) potassic (K-feldspar, biotite, chlorite, and epidote); (2) phyllic (quartz, pyrite, and sericite); and (3) propylitic (chlorite and epidote). In the potassic zone, according to Hollister and others (1974), sulfides are more abundant as disseminations than as veinlet fillings; however, veinlets become dominant in the phyllic zone. Molybdenum assays increase and copper assays decrease with increasing depth.

Cornelia Pluton, Arizona

Wadsworth (1968) concluded that a portion of the Cornelia pluton, exposed to the west of the New Cornelia mine, may be the eroded root zone of the New Cornelia porphyry copper deposit, which was downfaulted to the east. As described by Wadsworth, this portion of the composite quartz monzonite–granodiorite parent pluton has an equigranular texture, in contrast to the porphyritic texture of quartz monzonite and granodiorite within the mine. The proposed conduit rocks to the west of the mine show evidence of minor deuteric and retrograde propylitic hydrothermal alteration or mineralization and are related by Wadsworth to intrusive rocks exposed in the mine by structural relationships and corrosive textures.

Little Hill Mine Area

The Little Hill Mine area is located on the northwest flank of the Santa Catalina Mountains, Pinal County, Arizona, about 12 miles southwest of the San Manuel–Kalamazoo orebody (Fig. 1). Elevations in the area range from 3,800 to 4,400 feet.

Lithology

The oldest rocks in the vicinity of the Little Hill Mine area are Precambrian Pinal Schist, which crops out mostly south of the Mogul fault zone (Figs. 2 and 3). Precambrian Oracle quartz monzonite occupies most of the area north of the Mogul fault. Numerous aplite-pegmatite dikes are associated with the Oracle quartz monzonite. Near the Mogul fault, Oracle quartz monzonite has been cataclastically deformed and has been mapped as a unit here termed the "transition gneiss" (Durning, 1972). Apache Group sedimentary rocks of Younger Precambrian age (not shown on Fig. 2) lie unconformably on the Pinal Schist south of

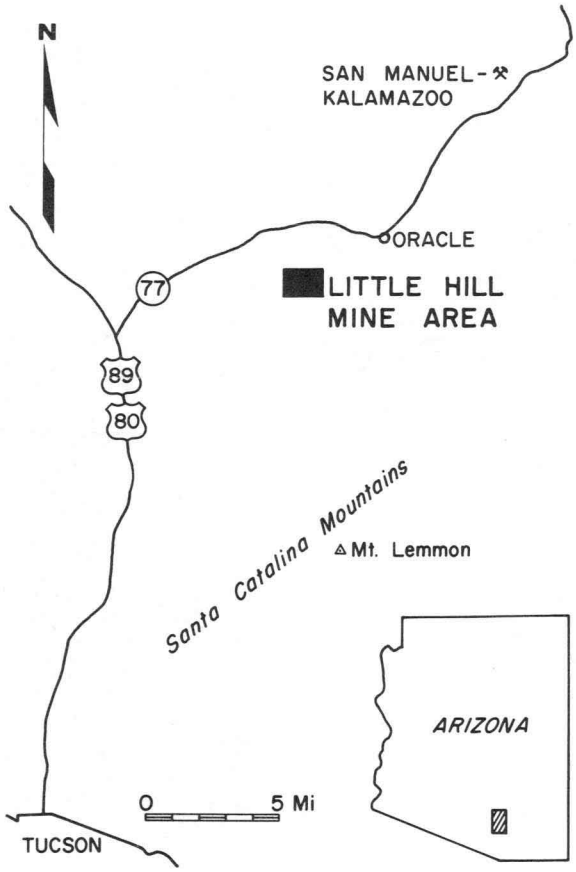

Fig. 1. Location map, Little Hill mine area, Pinal County, Arizona

the mapped area.

An intrusive body of coarse-grained, equigranular quartz monzonite has intruded the zone of deformation adjacent to the Mogul fault between the transition gneiss and Oracle quartz monzonite. This intrusive quartz monzonite has been dated by the Rb-Sr method at 163-303 m.y. The range is not unexpected because of the contamination of Laramide rocks which are intruded into this type of Precambrian environment, and the data actually favor a Laramide age for the quartz monzonite (D. E. Livingston, University of Arizona, oral communication, 1975).

The youngest rocks exposed in the vicinity of the Little Hill Mine are dikes of Tertiary age. Northwesterly trending rhyolite dikes that intrude the Oracle quartz monzonite are the most prominent and are possibly premineral. Latite, quartz latite, monzonite porphyry, and quartz porphyry dikes are also present but are of postmineral age.

Structure

The west-northwest-trending Mogul fault is the major structural feature in the vicinity of the Little Hill Mine. Fifteen hundred feet of left-lateral displacement on the fault in the Little Hill Mine area is suggested by the offset of a monzonite porphyry dike (Fig. 2).

Estimates based on interpretation of aeromagnetic data (F. P. Fritz, AMAX Exploration, Inc., oral communication, 1975) suggest that the fault has a minimum throw of 4,500 feet.

Alteration and Mineralization

At the surface in the vicinity of the Little Hill Mine, hydrothermal alteration and mineralization extend over an area roughly 8,000 x 4,500 feet. The alteration and mineralization are distributed among outer, middle, and inner zones (Figs. 4 and 5).

The inner, or core zone, is defined by the surface exposure of intrusive quartz monzonite. The core-zone alteration mineral assemblage consists of veinlet quartz, pervasive quartz, pervasive late-magmatic to hydrothermal veinlet-related sericite, and K-feldspar. Much sericite and secondary K-feldspar occur as envelopes adjacent to veinlets of hydrothermal quartz. Conspicuous K-feldspar occurs additionally as late-magmatic reaction rims between quartz and sericitized plagioclase. Retrograde chlorite alteration partially destroys primary and secondary biotite, and clay minerals commonly coat fracture surfaces.

Mineralization in the core zone consists mostly of pyrite, magnetite, and minor chalcopyrite associated with narrow quartz veinlets and as disseminations. Magnetite appears to be locally replaced by sulfides. Although quartz veinlets are abundant in the core zone, the average sulfide content is low, ranging from a trace to 0.75%. The range in copper values is 0.02–0.07%, and pyrite-chalcopyrite ratios range from 1:1 to 5:1. Molybdenite is present both in quartz veinlets and as disseminations in trace amounts.

Middle-zone alteration and mineralization are elongate in plan view, 5,000 x 2,000 feet, and extend easterly from the eastern exposed end of the Little Hill quartz monzonite (Figs. 4 and 5). The middle zone is well defined at the surface by rock-chip geochemical values for copper of more than 600 ppm.

The middle-zone alteration assemblage includes quartz, sericite, secondary K-feldspar, biotite, chlorite with leucoxene, minor epidote, carbonate and clay, and magnetite. Hydrothermal quartz occurs in veins and as a pervasive

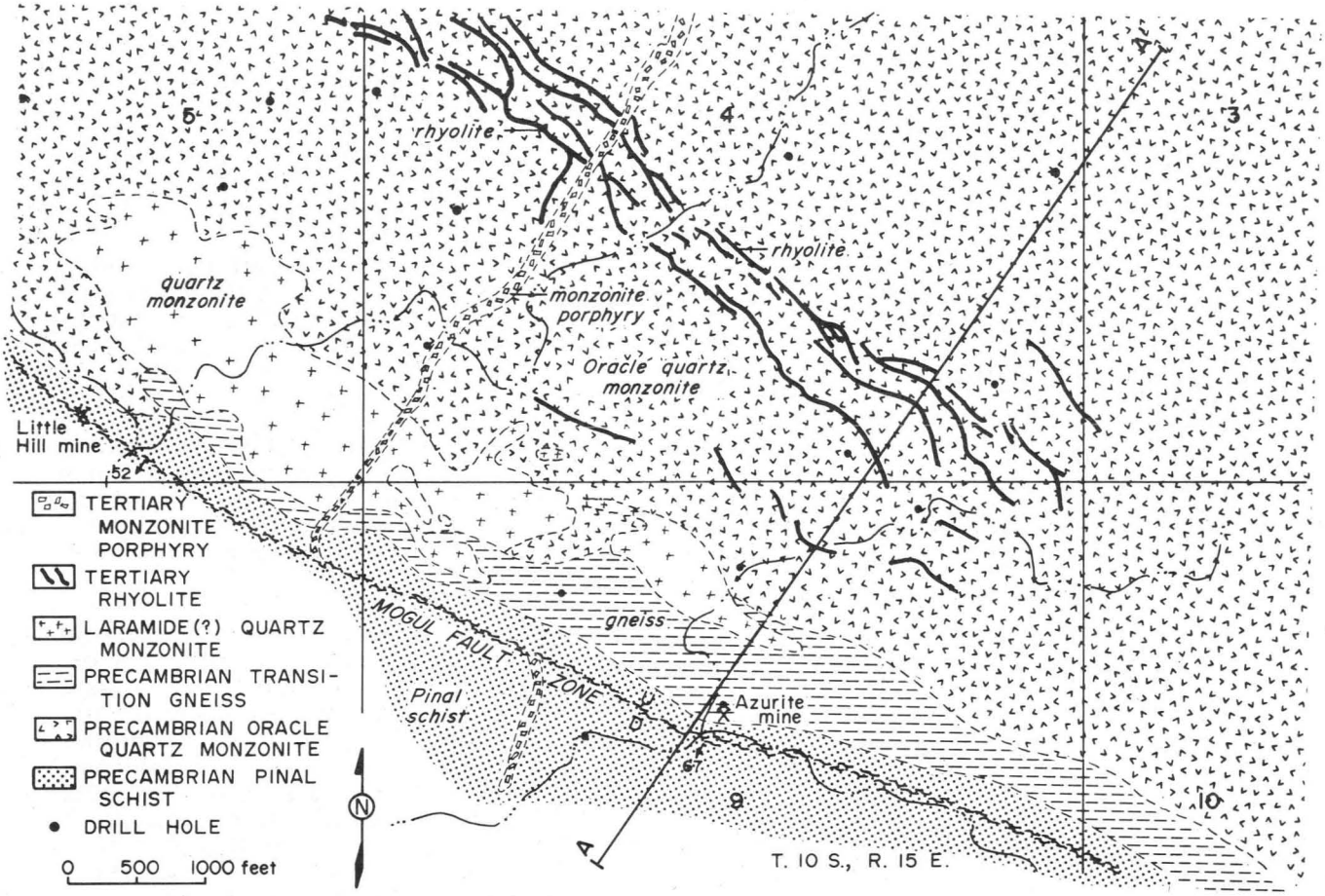

Fig. 2. Generalized geologic map, Little Hill mine area

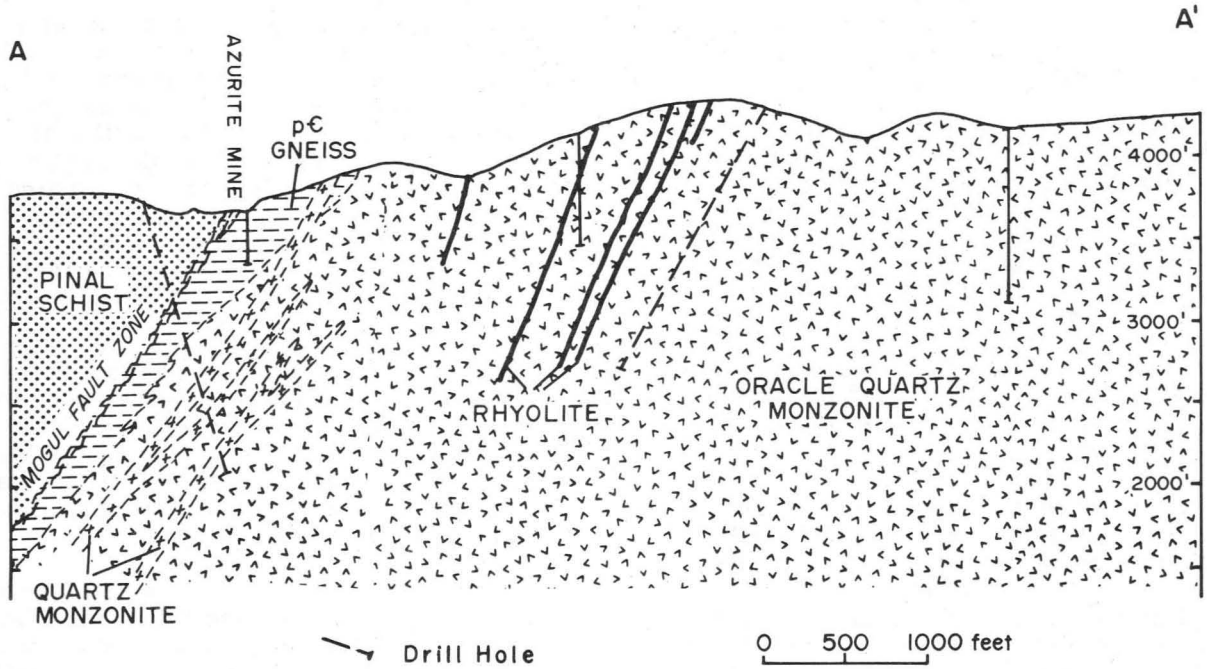

Fig. 3. Geologic cross section A-A', looking west

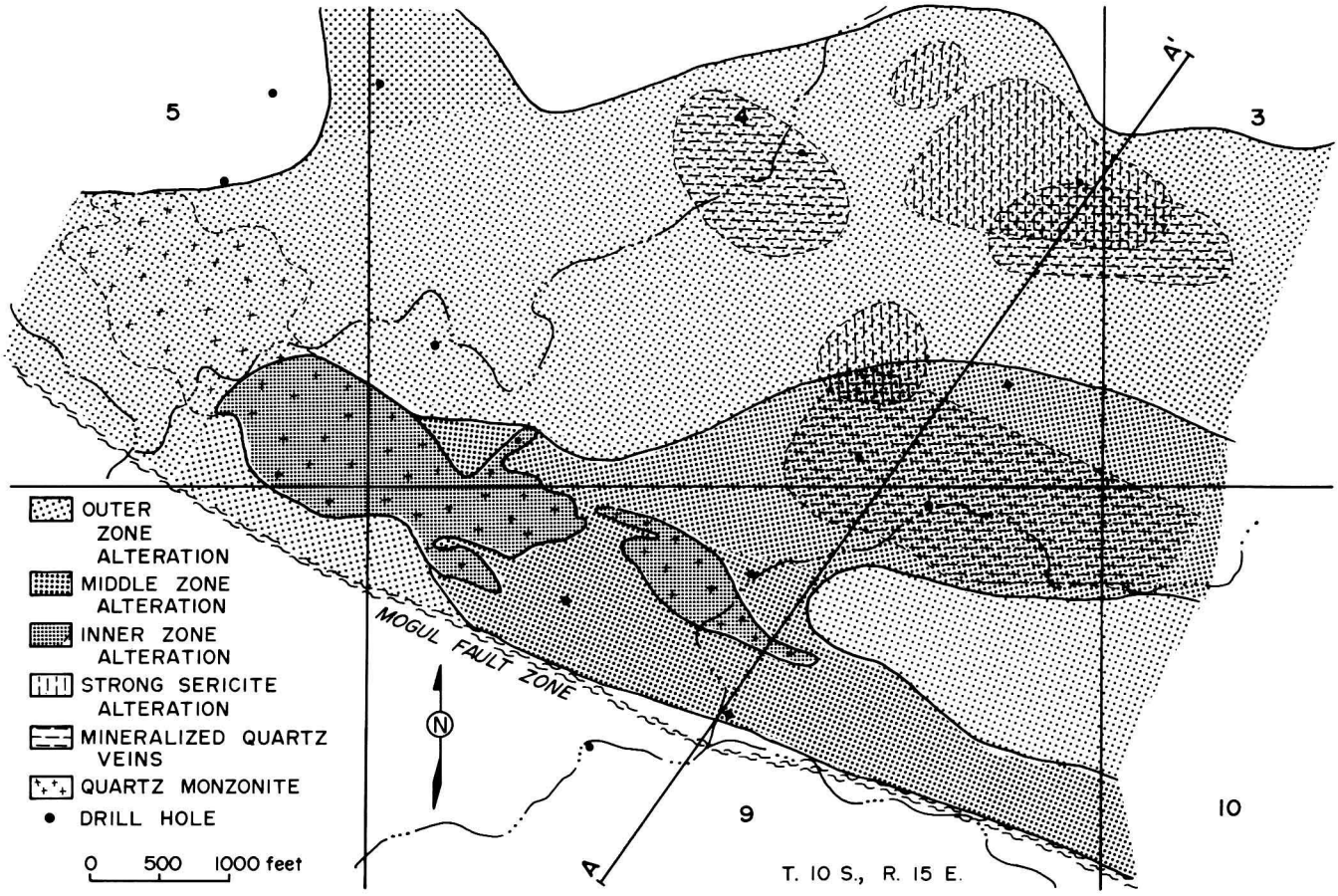

Fig. 4. Generalized alteration map, Little Hill mine area

flooding. Sericite commonly dusts plagioclase and envelops quartz veinlets. Secondary K-feldspar occurs in veins, as envelopes to quartz veins, and as local flooding. Fine-grained secondary biotite of late-magmatic to deuteric origin forms clotlike masses replacing plates of primary biotite and commonly is itself partially altered retrogressively to chlorite. Magnetite occurs with quartz in veinlets and with quartz and alkali feldspar in pegmatitic pods and lenses. Epidote, carbonate, and clay are not abundant and are mostly restricted to small, relatively late veinlets and fracture coatings.

Mineralization in the middle zone consists of spottily distributed pyrite, chalcopyrite, molybdenite, and magnetite. Copper values are highest in the middle zone. Seventy to eighty percent of the copper and molybdenum sulfide mineralization is fracture and veinlet associated; the remaining sulfides are disseminated. In the middle zone, pyrite-chalcopyrite ratios average 1:1 at the surface and increase with increasing depth to 4:1. Both copper and molybdenum values decrease with increasing depth, even though the quartz veinlets persist (Fig. 6). Magnetite fills microfractures and occurs in association with sulfide minerals in the quartz veinlets. Middle-zone copper values range from 0.10% to 0.25%; molybdenum values range from 10 to 50 ppm.

Outer-zone alteration and mineralization form a broad, diffuse, poorly defined envelope around the core and middle zones. Prominent alteration minerals in the outer zone include chlorite, epidote, sericite, quartz, magnetite, clay, and carbonate. Chlorite, locally accompanied by leucoxene, is the most conspicuous of these minerals and replaces a large percentage of the primary biotite. Epidote occurs both in hydrothermal veinlets and as a pervasive alteration product of primary biotite. Light, pervasive, probably deuteric sericitization of plagioclase is common. Relatively extensive development of sericite occurs adjacent to disseminated sulfides and as envelopes adjacent to hydrothermal quartz veins. Secondary quartz occurs mostly in veinlets and is often accompanied by finely divided magnetite. Clay and carbonate locally fill fractures.

Mineralization in the outer zone is dominated by pyrite, with minor amounts of magnetite, molybdenite, and chalcopyrite. Sulfide

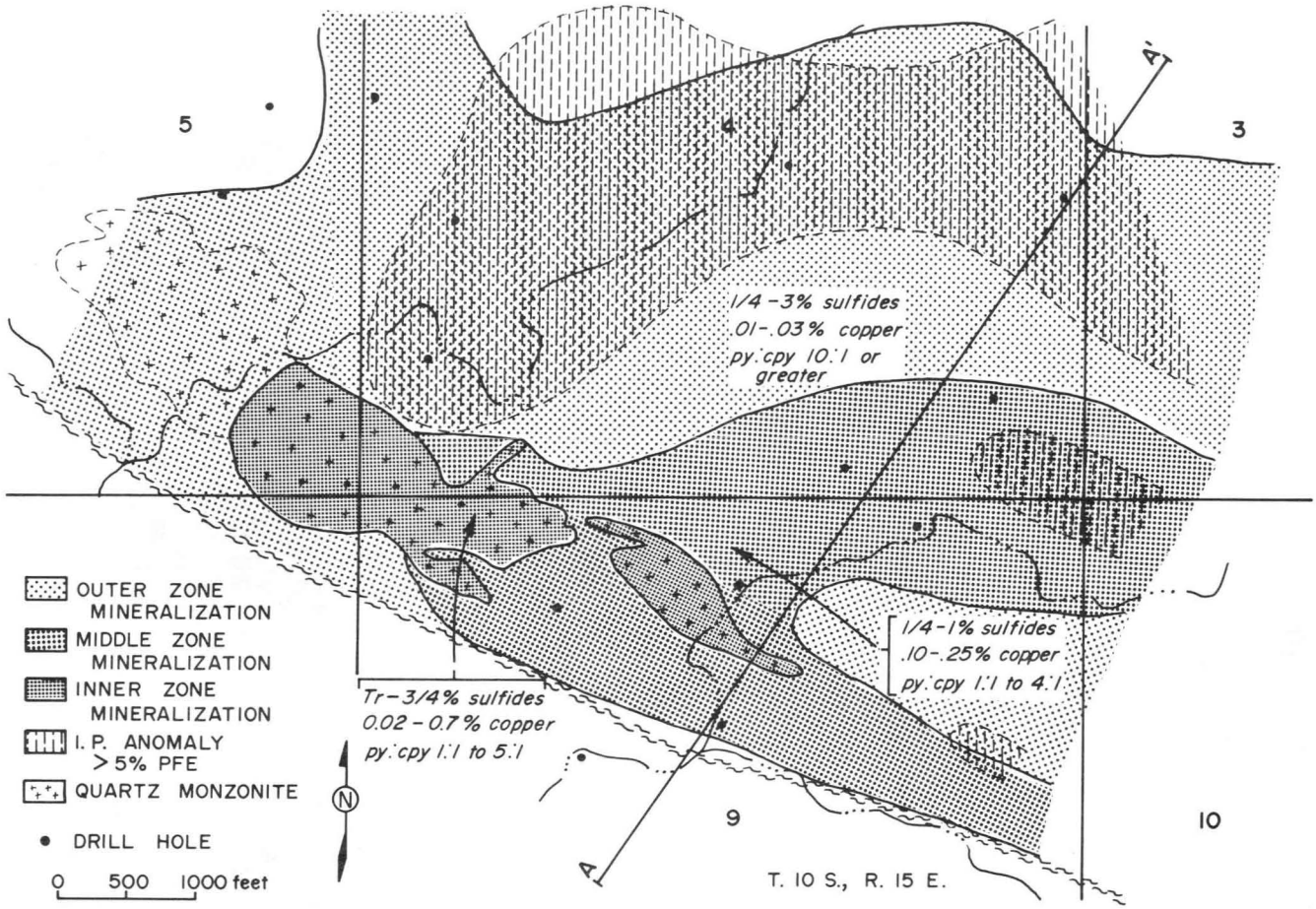

Fig. 5. Generalized mineralization map, Little Hill mine area

minerals are abundant as granules distributed throughout veinlet envelopes rather than as components of the quartz veins. Within the area of the induced-polarization anomaly (Figs. 5 and 6), total sulfide content of the rock averages 2-3 volume percent. Outside of the anomaly, the sulfide content is typically 0.5–1%. In the outer alteration-mineralization zone, pyrite-chalcopyrite ratios average 10:1 or greater. Copper concentrations range from 0.01% to 0.03%, and molybdenum in the outer alteration zone ranges from 10 to 50 ppm. Sulfide mineralization in the outer zone typically has an erratic distribution. A successive, retrograde onlap of outer, upon middle, upon inner alteration-zone mineral assemblages is apparent in the Little Hill Mine area. A similar retrogressive inward collapse of alteration-zone assemblages has been noted elsewhere (Davis, 1974) and seems to reflect the transition from late-magmatic to hydrothermal conditions.

Discussion

Several features of the Little Hill Mine area, when compared with well-known porphyry copper deposits, suggest that mineralization and alteration associated with the quartz monzonite intrusion along the Mogul fault may represent deep-level exposure of a porphyry copper system:

1. The intrusive quartz monzonite with which mineralization is associated has a phaneritic, equigranular texture suggestive of deep-level emplacement rather than a porphyritic texture indicative of hypabyssal emplacement.

2. The assemblage of alteration minerals —chlorite, magnetite, carbonate, quartz, epidote, sericite, and K-feldspar—is compatible with deep-level exposure of the system.

3. A low overall percentage of sulfides at the Little Hill prospect and the relatively high ratio of chalcopyrite to pyrite are consistent with an interpretation of deep-level exposure.

4. An absence of Pb-Zn-Au-Ag zoning, as determined from geochemical surveys in the vicinity of Little Hill Mine, is more typical of deep-seated or submarginal mineralization than of shallow porphyry system exposure.

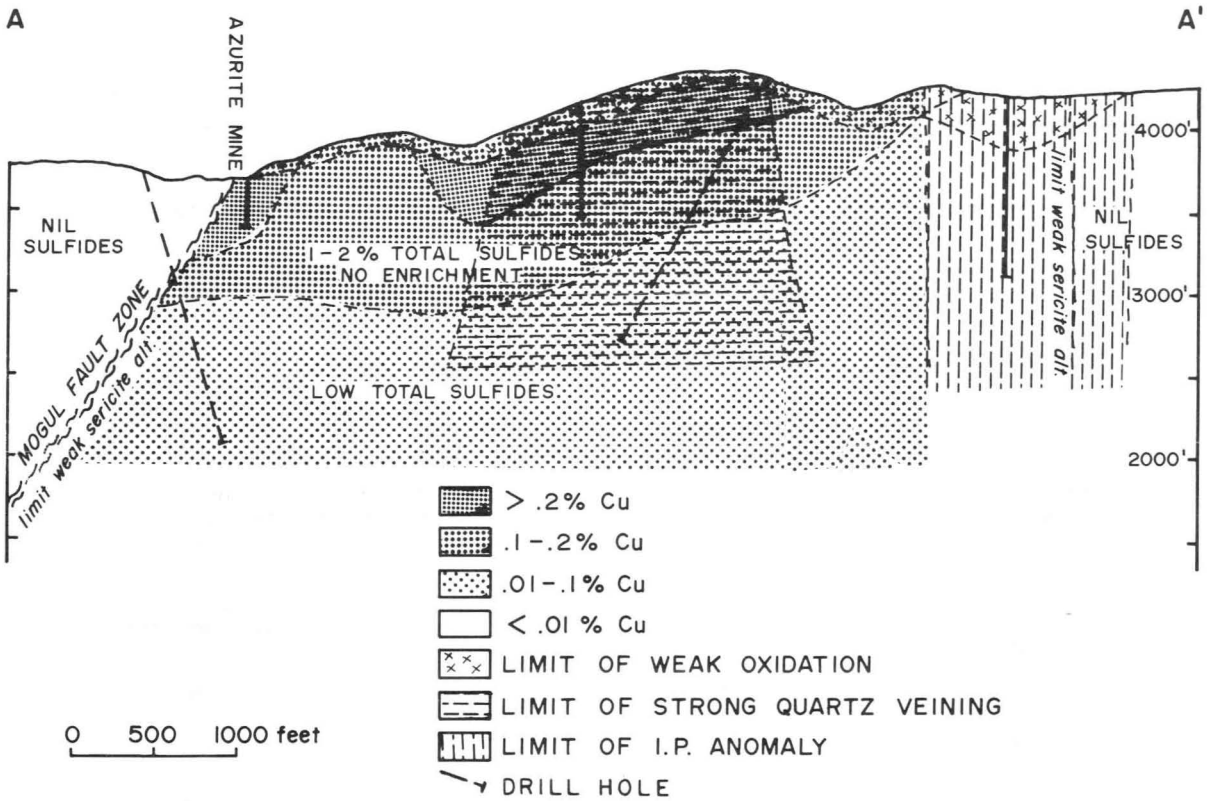

Fig. 6. Mineralization cross section A-A', looking west

At the Little Hill Mine, displacement along the Mogul fault and subsequent erosion have provided a deep, root-level exposure of a porphyry copper system. It must be stated, however, that evidence is lacking that would distinguish Little Hill as the root zone of an economically viable porphyry copper system from that of a submarginal porphyry copper system because the upper part of the Little Hill system has not been found. In the Little Hill porphyry system, crudely concentric shells of alteration and mineralization are centered around an intrusive body of quartz monzonite. With increasing depth, the intrusive rock appears to become more equigranular and alteration envelopes progressively diminish in size, extensiveness, and intensity. Concomitantly, the distinction between alteration envelopes becomes less well defined at greater depths owing to the merging of alteration assemblages. Mineralization is widely but irregularly distributed and diminishes with increasing depth. Secondary magnetite, in contrast, appears to be augmented with increasing depth.

Recognition of Root Zones of Porphyry Copper Systems

Superficial similarity of alteration and mineralization in hood-and root-level exposures of porphyry copper systems often permit their confusion. Specifically, root zones may be confused with the peripheral zone as described by Lowell and Guilbert (1970) at San Manuel–Kalamazoo or the weak potassic zone described by Corn (1975) at Red Mountain, Arizona. Ability to distinguish between root and hood exposures is of considerable importance in mineral exploration programs. If the surface or near-surface expression of a porphyry copper system is consistent with exposure of a root zone, the following conclusions may be inferred:

1. There is minimal justification for deep testing of the exposed mineralization.

2. Significant secondary enrichment is unlikely because of the low total sulfide content at deep levels of exposure.

3. If the root-zone exposure is related to uplift along a major fault, a portion of the productive part of the system may be preserved on the downthrown side of the fault.

4. Significant amounts of copper oxides may occur in the vicinity of the root zone because of the low initial pyrite-chalcopyrite ratios and the low overall sulfide content.

Table 1 enumerates comparative characteristics, both permissive and definitive, which

Table 1. Comparative characteristics of hood-level and root-level exposure of porphyry copper systems

Root Zone	Hood Zone
Texture and Structure	
1. Mineralization frequently associated with phaneritic equigranular intrusive rock	1. Mineralization associated with porphyritic intrusive rock
2. High proportion of disseminated sulfides have a bleblike, commonly syngenetic appearance	2. High proportion of sulfides occur in crosscutting, epigenetic textural modes
3. Veinlets relatively free of vugs	3. Veinlets commonly vuggy
4. Breccia pipes absent; relatively wide-spaced fracturing; sympathetic veining related to master faults	4. Breccia pipes may be present; abundant, closely spaced fractures; stockwork veining
5. Limited number of dikes associated with mineralizing intrusion	5. Abundant crosscutting dikes may be associated with mineralizing intrusion
Mineralization	
1. Mineralizing intrusion barren to weakly mineralized with sulfides	1. Mineralizing intrusion barren to well pyritized
2. Low overall sulfide content (generally less than 1% in the middle and inner zones; 1-3% in the outer zone); spotty distribution of higher sulfide values	2. Moderate to high total sulfide content (2-10%); widely distributed
3. Sulfide population dominated by pyrite in the outer zone; chalcopyrite/pyrite relatively high in the middle and core zones; molybdenite commonly present	3. Sulfide population dominated by pyrite; molybdenite typically absent
4. Copper mineralization decreases with increasing depth, although veinlets persist; molybdenum mineralization persists or in-increases with increasing depth	4. Copper and molybdenum mineralization typically increases with increasing depth
5. Original magnetite content of intrusive rock augmented by introduction of secondary magnetite in veinlets and as pervasive replacement product of ferromagnesian silicates; magnetite commonly replaces sulfides; relatively high magnetite-sulfide ratio	5. Secondary magnetite locally present, but overall augmentation of magnetite in the mineralizing intrusive rock is not pronounced; magnetite is replaced by sulfides; magnetite-sulfide ratio comparatively low
6. Pb-Zn-Au-Ag zoning typically absent or poorly developed	6. Pb-Zn-Au-Ag zoning commonly well developed
Alteration	
1. Alteration zoning is not well defined; core-zone assemblage consists of flood and veinlet quartz, reaction rim K-feldspar after particially sericitized plagioclase, veinlet K-feldspar, and epidote, chlorite and carbonate after biotite and hornblende; core zone transitional into middle and outer zones with gradual diminution of potassium metasomatism	1. Exposed alteration commonly consists of a single, dominantly propylitic mineral assemblage or of an inner phyllic assemblage enveloped by a propylitic assemblage; reaction rim K-feldspar absent; secondary alkali feldspar absent, or if present, albitic and veinlet related; plagioclase replaced by illite-sericite, carbonate, and epidote; ferromagnesian sillicates replaced by epidote, chlorite, and carbonate
2. Most extensively developed metasomatic alteration occurs immediately adjacent to veinlets; pervasively distributed alteration not strongly developed	2. Alteration distribution notably pervasive as well as veinlet related
3. Podlike, pegmatitic masses of quartz and K-feldspar with accompanying magnetite and sulfide commonly present	3. Pegmatitic mineralization absent

permit distinction between hood- and root-level exposures of porphyry copper systems. Not all characteristics are present in each deposit, but identification of several of these features is generally sufficient to permit confident distinction between root- and hood-zone exposure.

Conclusions

Study of alteration and mineralization exposed in the vicinity of the Little Hill Mine in southern Arizona suggests that it represents deep-level exposure of a porphyry copper system. An assemblage of attributes common to exposures of deep-level alteration and mineralization in porphyry copper deposits is identified. Recognition of these characteristics commonly permits distinction between the superficially similar appearance of hood-zone and root-zone exposures of porphyry copper systems.

Acknowledgments

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TECTONIC SETTING OF THE PORPHYRY COPPER DEPOSITS OF SOUTHEASTERN ARIZONA AND SOME ADJACENT AREAS

by

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Abstract

The major mineral deposits of southeastern Arizona and the adjacent parts of Sonora, New Mexico, and south-central Arizona occur in tectonically complex parts of the Basin and Range geologic province. This complexity is the cumulative result of at least three periods of severe and diverse kinds of regional deformation, as well as of some local disturbances. The oldest faults of the region are major northwest-trending basement flaws that were recurrently active. Next, the Laramide orogeny resulted in the development first of thrust faults and then of magmas and mineralizing fluids. Finally, the Basin and Range block faults formed. Although most of the major mineral deposits of the region, among them the renowned porphyry copper deposits, are temporally associated with the Laramide orogeny, they are spatially associated with the oldest faults. Furthermore, conditions arising from the youngest period of deformation have modified the deposits in many ways. A synthesis of the entire geologic development of the region thus is a vital key to understanding at least the distribution of the major ore deposits, if not also some of their individual features.

During the Precambrian, at least some of the major northwest-trending faults were formed in what are now the crystalline basement rocks. This early movement and some subsequent movement probably was left slip, and the amount of the earliest horizontal movement on one fault may have been about 15 km (10 mi). Some faults of this system were activated or reactivated during the Triassic, Jurassic, and Early Cretaceous; many of them were reactivated during the Paleocene; and some segments were reactivated during mid-Tertiary and even later times. These northwest-trending basement flaws were probably the main conduits for upward-moving magmas and mineralizing fluids at least since the Triassic, for many stocks were emplaced along the faults and all major mineral deposits lie within a few kilometres of the faults. A critical feature of these faults is that they were not active synchronously in Triassic and younger times, but that they did provide a structural anisotropy which guided the development of many subsequent features. Consequently, the geologic record varies, not only from fault to fault, but also from one segment of a major fault to another. Under these circumstances it is no wonder that their extent and perhaps their significance has not been fully appreciated, although they have been flagged by such workers as Harrison Schmitt, Kenyon Richard, Harold Courtright, and Evans Mayo.

During Late Cretaceous time, and perhaps somewhat later toward New Mexico, a regional thrust sheet formed near the surface in response to northeast-directed compressive stress. The allochthon extends northwest, west and south of the Little Dragoon Mountains near Benson, Arizona, and it extends east at least to the New Mexico border, about 15 km (10 mi) south of Interstate Highway 10, and probably on eastward to the El Paso area. The allochthon consists of several subordinate thrust sheets that are broken by many minor thrust faults, tear faults, and disharmonic normal faults; locally the thrust sheets are also folded.

The role of the thrust faults in the distribution of the major mineral deposits is secondary to that of the northwest-trending basement flaws, apparently because the thrust faults were relatively shallow features. In most places mineralization and plutonism of Laramide age followed the period of major thrust faulting. That being the case, the actual amount of northeastward thrust movement is of little consequence to the mineralization. Major orebodies probably occur in the allochthon because it was present in the zone of appropriately decreasing pressure and temperature near the surface and because it contains many rocks having a composition favorable to mineral deposition. However, in some mining districts,

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such as Tombstone and Helvetia, the minor structures related to the thrust faults produced second-order and third-order conduits for mineralizing fluids migrating away from the master faults as they moved upward. Nevertheless, the thrust faults and mineralization may be related indirectly, for the compressive deformation of the rocks at the surface is probably genetically linked to the generation of magma and mineralizing fluids at depth through the underthrusting of an extensive crustal plate. Further speculations in this direction are more appropriate to the tectonic synthesis of a much larger region than southeastern Arizona.

During Oligocene and later time the region was deformed again, this time in response to east-west-oriented tension. This stress condition led to the development of normal faults, grabens, and tilted blocks typical of the Basin and Range province, and it permitted upward movement of additional magma and locally also of some ore fluids. In a few places domes of gneiss and fault blocks were raised. Where older faults were suitably oriented, the normal faults were deflected from a north-south orientation. Thus, some segments of the basement flaws were reactivated as normal faults. Some of the uplifted areas rose so rapidly and so far that the gross topographic imbalance led to gravity sliding and low-angle normal faulting. Where the gravity faults were subparallel to thrust fault segments these segments were reactivated. Where the gravity faults cut rocks that were previously thrust faulted, intruded, or mineralized, the earlier features were moved piggyback fashion by the younger gravity faults, such as happened on the San Xavier fault on the east flank of the Sierrita Mountains and in the Rincon Mountains. This last period of major deformation, then, guided the development of the present topography, helped to determined the depth of exposure or of burial of mineral deposits, and influenced the development and distribution of secondary mineralization.

From the foregoing review of the tectonic development of southeastern Arizona and the relations between this development and mineralization several conclusions may be drawn: (1) In order to understand the distribution of the major mineral deposits both the regional geology and the local geology near the deposits must be known; it is as important to know the total geologic development of an area as it is to know just the events of the period of major mineralization. (2) In southeastern Arizona and adjacent areas the distribution of the northwest-trending basement flaws appears to be a key to the distribution of the major orebodies. The most favorable segments for mineralization are those which contain a scattering of intrusives and host rock alike, not those which are obliterated by intrusive bodies or devoid of such bodies. Geophysical methods may be useful in testing the presence and distribution of the master faults herein outlined, for even where concealed they may separate rocks of contrasting geophysical signature. (3) Prime ground for mineralization typically lies in favorable rock along secondary structures a few kilometres from the master faults. Perhaps a systematic study of the direction of ore fluid movement and of the optimum distance from the master faults (and/or depth at which mineralization occurred) would provide guidance to further restricting exploration targets. (4) More must be learned of events and conditions at the depths in which ore fluids and metal sources arise, so that regional tectonic patterns may be better utilized in economic exploration.

STRUCTURAL RECONNAISSANCE OF THE SOUTHWEST PORPHYRY COPPER PROVINCE

by

Thomas W. Mitcham [1]

Abstract

Faults have been recently mapped on a number of quadrangles of various sizes in Arizona and New Mexico, using photogeologic techniques applied to high-altitude and hyperaltitude imagery. The results suggest that faults are much more numerous and interconnected and more commonly recurrent than indicated by most published maps and that fault systems are more variable than generally recognized, strikes being variously sinuous, arcuate, circular, and irregular as well as relatively straight.

Mapping Techniques and Data Display

The reconnaissance mapping being reported essentially involves mapping of faults from synoptic views presented on available AMS high-altitude photographs (e.g., Fig. 1) and Landsat MSS Band-5, B&W imagery (e.g., Fig. 2). Both of these types of imagery were used on some quadrangles.

Observational techniques applied have evolved from geologic studies on high-altitude photography by the investigator over a period of two decades, based on ground-level mapping over a period of three decades. Apparently, the now-obvious geologic advantages of synoptic views were first recognized in an Arizona Geological Society paper (Mitcham, 1959). Fault observations are plotted by inspection onto USGS topographic base maps, variously 8.5-minute, 15-minute, and 1 x 2-degree quadrangles.

The reconnaissance has involved fault mapping of 27 quadrangles (24 within the Southwest porphyry copper province and 3 on adjoining portions of the Colorado Plateau) during the past five years, but only two quadrangles are reproduced for this paper because of proprietary considerations. As illustrated in Figures 1 and 2, an attempt is made to express order of magnitude of fault movement by weight of line. Solid lines designate indicated faults and dashed lines inferred faults. Both maps have been sample field checked; that is, field checking has been accomplished for only several selected key areas on each map.

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Fault Density

A perusal of the 27 newly mapped quadrangles suggests that, generally, fault density (in terms of miles of fault trace per square mile) greatly exceeds that indicated by published maps. This should be no surprise to those who have conducted detailed geologic mapping within mining districts where numerous faults not detected on the undisturbed surface are readily revealed by exposures in underground workings.

Measured average fault densities within selected quadrangles are listed in Table 1. These are considered to be minimum figures because more intensive mapping would probably increase mapped fault density for each quadrangle.

Some of the variations in fault density in the selected tabulation are due to quadrangle scale; that is, fault details are mapped with greater facility at larger scales. The Santa Rita quadrangle is a special case, as explained under a subsequent heading, and this accounts for the rather high fault density on the published map of this quadrangle.

Considering the quadrangles mapped during this reconnaissance as a sample and allowing for extrapolation into areas of thick valley fill, the density of fault trace for the portion of Arizona within the Southwest porphyry copper province would be at least 800 miles per 15-minute quadrangle and for the Colorado Plateau portion about 100 miles per 15-minute quadrangle. This suggests that the total length of fault trace in the state is at least 220,000 miles. Order of magnitude of the faults is not considered, of course, in arriv-

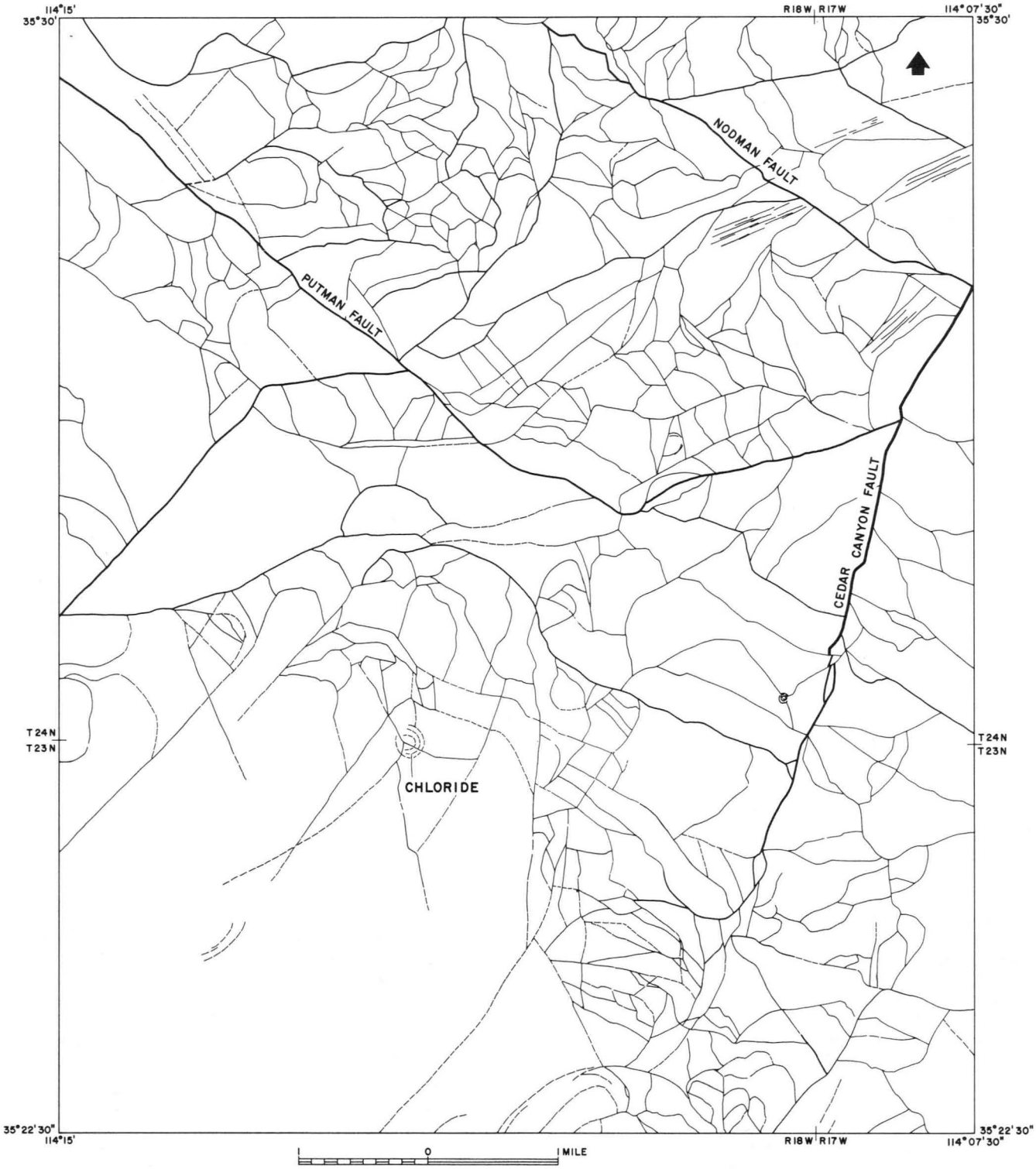

Fig. 1. Fault map, Chloride 7.5-minute quadrangle, Mohave County, Arizona. Mapping from AMS high-altitude photographs (Mitcham, 1974).

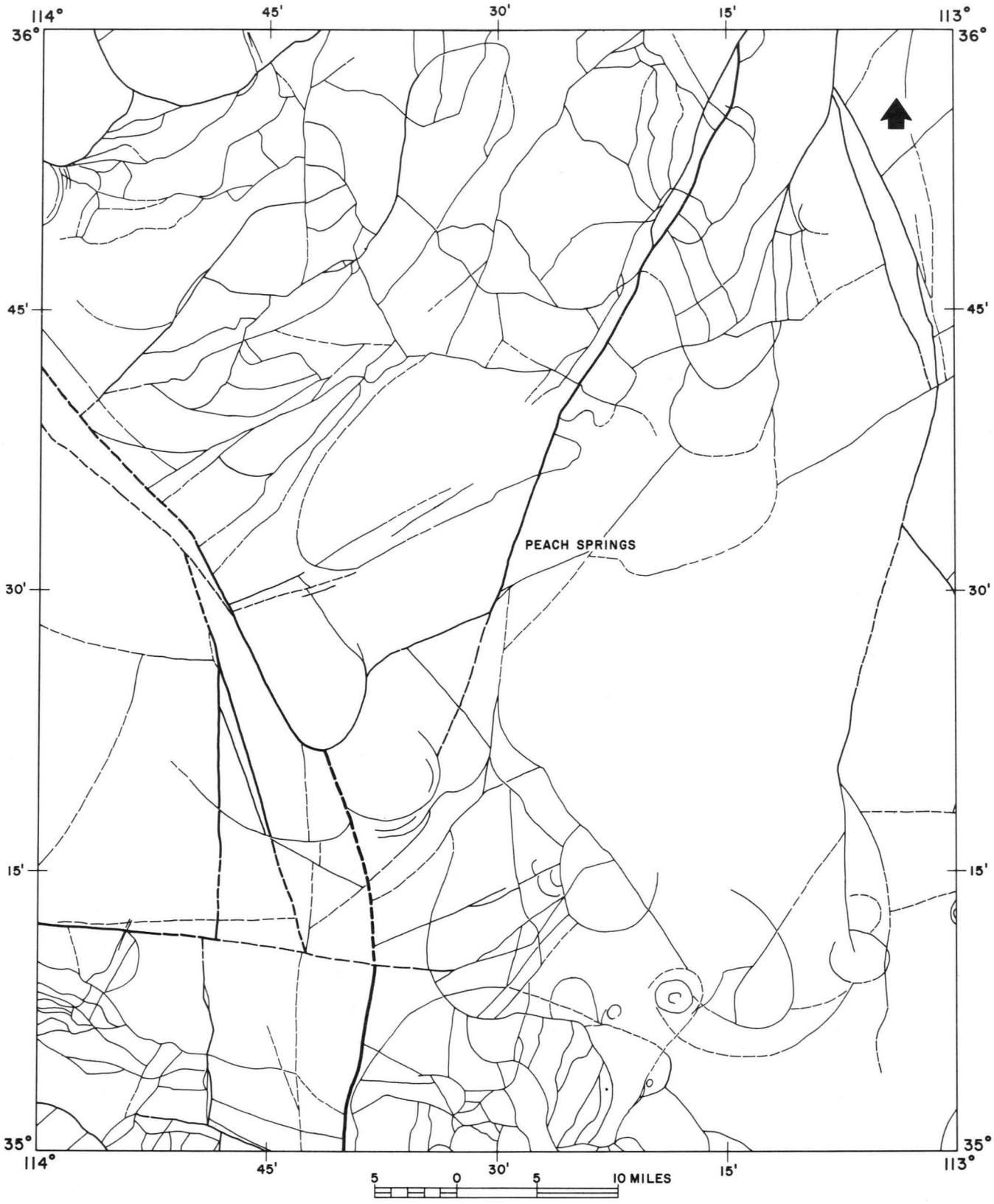

Fig. 2. Fault map, Peach Springs 1-degree quadrangle (west half Williams 1 x 2-degree quadrangle), Coconino, Mohave, and Yavapai Counties, Arizona. Reconnaissance mapping from Landsat MSS Band-5, B&W imagery (Mitcham, 1974).

Table 1. Fault densities for some quadrangles in the Southwest porphyry copper province

Quadrangle	Size	Fault Densities (miles of trace per square mile)	Source
Chloride, Arizona	7.5'	5.40	this reconnaissance
Clifton, Arizona	15'	3.31	this reconnaissance
Grand Canyon-Williams, Arizona	1x2°	0.38	this reconnaissance
Haunted Canyon, Arizona	7.5'	7.68	this reconnaissance
Haunted Canyon, Arizona	7.5'	1.90	Peterson (1960)
Santa Rita, New Mexico	7.5'	3.95	Jones and others (1967)

ing at this estimate. However, it may be of interest to note that the figure is about 100 times the total miles of fault trace displayed on a tectonic map of Arizona by Wilson and Moore (1959, Fig. 12).

Patterns in the Southwest Porphyry Copper Province Fault System

Faults in the Southwest porphyry copper province are intricately and almost completely interconnected (Figs. 1 and 2). Regardless of the strike length of a given fault (hundreds of feet or over 100 miles), at least one of its terminations intersects another fault. The entire province fault system can be described as one of hundreds of thousands of miles of strike length of intricately interconnected faults that form a pattern in which every compass bearing is represented and most are widely represented, even though strikes within certain sectors (e.g., north, northwest, or northeast) tend to be dominant in various portions of the province and over the entire province.

In pattern, strikes of faults in the province are variously sinuous, arcuate, circular, and irregular as well as relatively straight. The wide variation in strike patterns of faults is not particularly surprising. This investigator has observed the same phenomenon in other regions, for example, the Midcontinent region where he has mapped a number of quadrangles. Other investigators are reporting the same or a very similar phenomenon (e.g., Gedney and others (1976) in south-central Alaska, Peterson (1976) in Nebraska, Kansas, and Iowa, and Smith (1976) in Utah, Nevada, and southern California).

A number of explanations have been attempted for circular or arcuate fractures or faults, which are frequently concentric or overlapping. These vary from meteoric impact to collapse following doming as a result of igneous intrusion (Smith, 1976). True explanations probably vary from structure to structure. In any case, detailed field investigations are needed to better understand these types of structures.

Two possibilities worthy of consideration are that the arcuate or circular structures are the result of collapse into openings resulting from differential movements at fault intersections or at points of strike change (Mitcham, 1974) or that they are the roots of old caldera structures. The latter explanation could provide a solution to the problem of locating Laramide volcanic centers, thus meeting the challenge of a way to find Laramide porphyry coppers as suggested by Elston (1970).

Recurrent Nature of Faults

The investigator is inclined toward the concept that a large percentage of faults in the province (and elsewhere) are recurrent over extensive periods of time. In an exaggerated way, this can be expressed as "once a fault, always a fault." This inclination is based on theory, the observational record, and the frequent notation during this reconnaissance of common fault patterns in adjoining, sharply contrasting terranes.

Theoretical Considerations

Once a region or area has been subjected to differential stress resulting in strain to the point of significant rupture (fracturing), further differential stresses at that point in time tend to be released by movement on the fractures (i.e., by faulting). This original faulting will develop some additional faulting, referred to as second-order faulting, third-order faulting, etc. To some extent, this original period of differential stress (orogeny) should determine the positions of faults and fault patterns "for all time" because in subsequent

periods differential stresses will tend to be released by movement on existing faults, even though the principal stress axes may be of substantially different orientations. This is to say that after the first major tectonic disturbance or orogeny in a region the region or area has become so anisotropic on a major scale that strain buildup to the point of significant new rupture is attained with difficulty.

The Observational Record

The concept that faults are commonly recurrent is difficult to test observationally because the data critical to this test are only rarely available due mainly to paucity of exposure of faults. Perhaps in some areas the faults are exposed but mapping has not been done in sufficient detail to allow adequate gathering of the critical data. In at least certain localities where adequate data critical to testing for the recurrent nature of faulting are available and have been carefully gathered faults have been established as being recurrent.

For example, evidence of recurrent movements on inherited Precambrian fault zones is prolific in the outcrops of the Grand Canyon (Huntoon, 1974), where a thick stratigraphic section with good marker beds is well exposed and where careful, rather detailed mapping has been done.

Another example worthy of citing is the Ground Hog-Ivanhoe-Lovers Lane fault, which is the major fault and probably the master mineralizer in the Santa Rita district, New Mexico. A total of five periods of movement are established (proved) for this fault, two being preore and three being postore (Lasky, 1936; Lasky and Hoagland, 1949; Jones, Hernon and Moore, 1967). Two additional periods of movement are likely; that is, the total periods of movement on this master fault may be as many as seven. The total net slip on the fault is about 3,500 feet, and the total throw is as much as 1,600 feet locally (Lasky and Hoagland, 1949). Many other faults in the district are also demonstrably recurrent (Jones and others, 1967).

The body of critical data on the Ground Hog-Ivanhoe-Lovers Lane fault, at least on the Ground Hog segment of it, is so comprehensive that the fault may rank as the most thoroughly measured fault in the world because of a rather unique set of favorable circumstances, geologic and otherwise.

The stratigraphic section within the Santa Rita district, although involving many systems and series from Precambrian through Tertiary, is relatively thin and contains many excellent marker beds. This section is inflated by a number of sills, some of which also provide good markers. Furthermore, the sequence of dikes and other intrusions, which represent perhaps as many as 29 time-distinct intrusive events, also assists in the relative dating of fault movements.

Added to the geologic circumstances that are highly favorable to readings on faults is the fact that geologic exposures are numerous in the various mine workings and in very numerous core holes within the Santa Rita district, including those of the Ground Hog mine. The key data base of the district is also greatly enhanced by perhaps as many as 100 man-years of geologic observations especially considering that a large number of the observers involved have been highly competent men. This investigator would mention Sam Lasky in particular as the keenest geologic observer he has ever had the good fortune to know.

The recurrent nature of faulting is almost the rule in the Santa Rita district. Considering that the tectonic history here is essentially the same as that of the Southwest porphyry copper province, would not this rule also apply to the province if a set of circumstances as favorable to critical data assembly in this district applied to the entire province?

Faults and Contrasting Terranes

Observations in a number of quadrangles mapped during this reconnaissance demonstrate that the strikes of faults and fault patterns do not usually change from one terrane to an adjoining contrasting terrane, for example, where an area of isoclinally folded Precambrian schist adjoins an area of flat-lying Miocene ash flows. Also, the tracing of established premineral faults from areas of older, premineral rocks into younger, postmineral rocks is frequently possible. Both of these observations suggest recurrent faulting.

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THE SAN XAVIER FAULT, PIMA MINING DISTRICT, ARIZONA

by

Louis J. Jansen[1]

Abstract

The San Xavier fault is a low-angle, undulating surface underlying approximately 50 square miles of the northeastern pediment of the Sierrita Mountains, south of Tucson, Arizona. This fault has long been recognized as a major postmineral structure separating ore-bearing rock in the upper plate from barren rock in the lower plate, or footwall. Three large open-pit copper mines (Mission, Pima, and San Xavier North) and numerous smaller underground mines are located in the upper plate.

The upper plate includes Precambrian granite, Paleozoic and Mesozoic rocks, Laramide quartz monzonite porphyry, and the Helmet Fanglomerate. The thickness of this upper plate ranges from a few tens of feet along the outcropping portion to approximately 2,000 feet in the central trough. The lower plate is dominantly Precambrian granite and granodiorite.

The Helmet Fanglomerate crops out in the southern part of the upper plate north of Twin Buttes. The location of the Helmet Fanglomerate roughly coincides with the central trough of the San Xavier fault, and this fault forms the basal contact of the fanglomerate.

The outcrop of the south and west margins of the fault is roughly arcuate shaped, opening to the northeast. A structural contour map of the fault surface, based on several hundred drill-hole penetrations, reveals a central, northeast-plunging trough, with steeper dipping southern and western flanks. As presently delineated, the fault extends north from Twin Buttes approximately 8 miles and is about 6-8 miles across the widest portion.

There are two published hypotheses regarding the age and direction of movement of the San Xavier fault and the formation of the Helmet Fanglomerate. The first (Cooper, 1960) proposes that the upper plate moved northward approximately 6 miles from the area of Twin Buttes during post-Helmet time. The second (Weaver, 1965) proposes gravity sliding of the upper plate to the east into a tectonic basin being formed by the rising Sierrita batholith. The Helmet Fanglomerate was later shed into the same tectonic basin onto the upper plate. A recent paper (Lukanuski, 1975) suggests that the Helmet Fanglomerate and other similar formations in southern Arizona were formed in rapidly developing, local tectonic basins undergoing tilting.

Comparison of geologic features in the upper plate with the area south of Twin Buttes, microstructures in the Helmet Fanglomerate, and the basal fault contact of the Helmet Fanglomerate favor a northward direction of movement in post-Helmet time or perhaps contemporaneous with Helmet formation.

The record of geologic events in this part of the Pima mining district includes preintrusive, premineral faulting and folding with a general northwest trend, Laramide intrusion and mineralization, development of the San Xavier fault and northward movement of the upper plate, and high-angle normal faulting of the upper plate and the San Xavier fault.

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THE GEOLOGY OF THE SAN XAVIER NORTH PORPHYRY COPPER DEPOSIT, PIMA MINING DISTRICT, ARIZONA

by

John R. King [1]

Abstract

The San Xavier North porphyry copper deposit is located on the Papago Indian Reservation, about 15 miles south of the city of Tucson. Events that led to its development began in 1955 when Asarco geologists discovered two small altered and mineralized outcrops surrounded by alluvium. Exploration drilling began in mid-1957 after successful competitive bidding with the Papago Indians. By 1967 over 60 holes averaging between 600 and 700 feet deep were drilled in the deposit. Initial production began in 1968 with the mining of copper-bearing silica flux for use at Asarco smelters. Production of copper oxide ore began in 1973 at an approximate rate of 4,000 tons per day.

The San Xavier North porphyry copper deposit consists of oxide copper zones, supergene chalcocite, and hypogene sulfides all contained within Cretaceous clastic rocks and Laramide quartz monzonite porphyry intrusions. The clastic rocks are an intimately interbedded sequence of arkosic sandstones, siltstones, and mudstones and are part of the Cretaceous Bisbee Group probably equivalent to the Amole Arkose. The sedimentary rocks were asymmetrically folded prior to the intrusion of the quartz monzonite porphyry.

The quartz monzonite porphyry exists as dikes and a single stocklike(?) mass which lies immediately to the south of the pit. The porphyry intrusions at San Xavier North are identical to the quartz monzonite porphyries at Mission and similar to the quartz monzonite porphyry described at Twin Buttes.

The only major fault delineated to date is the low-angle, mid-Tertiary San Xavier fault. The depth to this structure is slightly over 2,000 feet and it forms the boundary between the overlying mineralized rocks and underlying unmineralized Precambrian granite.

Hydrothermal mineralization and alteration at San Xavier North are spatially interrelated and formed as part of a continuing chemical process that resulted in a zonal distribution of both sulfide and alteration minerals. Hypogene ore-grade (approximately 0.5% Cu) mineralization is confined to the clastic wall rocks in such a manner as to form an arcuate zone adjacent to the main porphyry mass. This ore zone mineralization is characterized by 1-3 percent by volume sulfides with a pyrite-chalcopyrite ratio that ranges from 1:1 to 1:3. Stratigraphy exerts an important control on the distribution of chalcopyrite in that the finer grained the sedimentary host is the greater the chalcopyrite content. Molybdenum and silver mineralization is concentrated within this ore zone and in the central porphyry mass.

Surrounding the ore zone is an area of pyrite mineralization that is characterized by a sulfide content of 2-4 percent and a pyrite-chalcopyrite ratio that ranges from 10:1 to 3:1. The area of change from the ore zone to the pyrite zone is transitional over a distance of nearly 100 feet.

Associated with both of the above-mentioned mineral zones is a phyllic alteration which in itself is internally zoned in a manner sympathetic to the described mineral zones. The strength of phyllic alteration is greatest in the pyrite shell at or near its interface with the chalcopyrite zone. Quartz veining is most abundant in the ore zone.

Supergene mineralization at San Xavier North consists of leached capping, two different oxide copper zones, and an ore-grade chalcocite blanket. An upper zone of oxide copper is contained within the capping and represents oxidation of a chalcocite zone that hung up dur-

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ing leaching of other sulfides. A lower zone of oxide copper exists at the base of the capping and is a product of partial oxidation of the main chalcocite blanket. The chalcocite blanket does not conform to bedrock topography and the eastern part of the enriched zone is partially oxidized and eroded. The chalcocite blanket ranges from 30 to 100 feet in thickness and is the result of approximate twofold enrichment. Copper grades in the blanket average between 0.6 and 1.0% Cu. The copper oxide zones consist of a mixture of chrysocolla, malachite, neotocite, melaconite, and minor azurite. The oxide copper grade is approximately 0.8% Cu.

Current interpretations are that the formation of the supergene deposit occurred prior to or during the formation of the mid-Tertiary Helmet Fanglomerate. Erosion and partial oxidation occurred after initial movement on the San Xavier fault and prior to deposition of the alluvial gravels that to a great extent preserved the deposit.

GEOLOGY OF THE CYPRUS PIMA MINE, PIMA COUNTY, ARIZONA

by

Joseph D. Langlois [1]

Abstract

The Cyprus Pima copper deposit, Pima County, Arizona, has recorded a production of over 146 million tons of ore since discovery in 1950. Orebody host rocks include altered Mesozoic arkose and siltstone and Paleozoic silty to sandy limestone altered to hornfels and tactite. The sedimentary section has been intruded by an early Tertiary quartz monzonite porphyry. Subsequent to the intrusion and formation of the orebody, the mine vicinity was intruded by thin, mid-Tertiary andesite dikes. The area was then buried by late Tertiary to Quaternary conglomerate and alluvium.

Intense preore and postore structural deformation has affected the deposit. Preore fracturing is demonstrated by the stockwork pattern of mineral distribution in the host rocks. Postore deformation is also present along both high- and low-angle faults. Some low-angle faults in the mine vicinity truncate ore horizons, and other low-angle structures may have as much as 10 km of displacement.

The orebody is dominantly a primary chalcopyrite deposit with by-product molybdenite. The bulk of ore tonnage is produced from the Mesozoic clastic section, and the higher grade sections in the deposit tend to be located in tactite zones. Major controls for the distribution of the orebody are structural and lithologic.

Introduction

The Cyprus Pima mine is located in the Pima mining district (Fig. 1) approximately 20 miles south of the city of Tucson in Pima County, Arizona. Situated on the eastern pediment surface of the Sierrita Mountains, the Cyprus Pima mine is a significant producer in one of the largest porphyry copper districts in the United States, with a districtwide rated production of about 200,000 tons of ore per day (Heinrichs, 1976).

Previous Production and History

The Pima mining district has had a long and varied history of activity extending back to Spanish colonial times. In 1872 the first mining claim in the Arizona territory, the San Xavier, was located in the Pima mining district to the west of the present Cyprus Pima mine. Early production in the district was supplied by small producers shipping ores containing silver, copper, zinc, gold, lead, and molybdenum. These ores were obtained from underground operations mining small

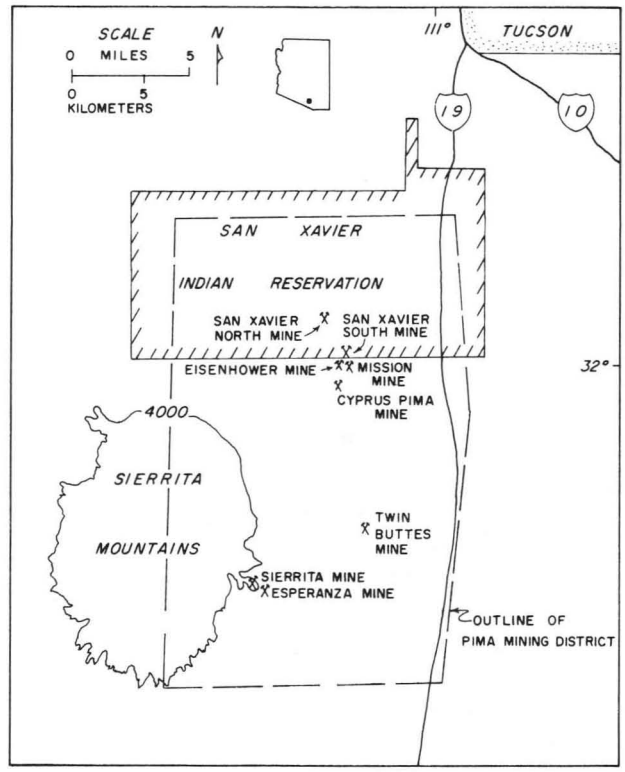

Fig. 1. Location map for Cyprus Pima mine

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tonnage replacement and contact metamorphic deposits.

Interest in the present Cyprus Pima mine was initiated at the suggestion of Dr. B. S. Butler, a renowned economic geologist at The University of Arizona. Based in part on this suggestion, United Geophysical Company decided to test and evaluate this property where it was believed that geophysical methods might provide useful exploration tools (Heinrichs, 1976). Prospecting permits for the area were obtained in 1950, and an exploration drilling program based on geological and geophysical factors was begun. Shortly thereafter, the first discovery hole was completed and after continued exploration a decision was made to develop a small underground mine.

In 1952 the first shipments of ore were made to smelters, and in that same year United Geophysical Company was acquired by the Union Oil Company. In 1955 the Union Oil Company sold a half interest in the underground mine to Cyprus Mines Corporation and also sold a quarter interest to Utah International Corporation. During the same year a decision was made to convert from underground to open-pit mining operations. Various expansions of the open-pit operation have resulted in a current capacity of 53,500 tons of ore per day. At present over 146 million tons of ore have been produced since the beginning of operations.

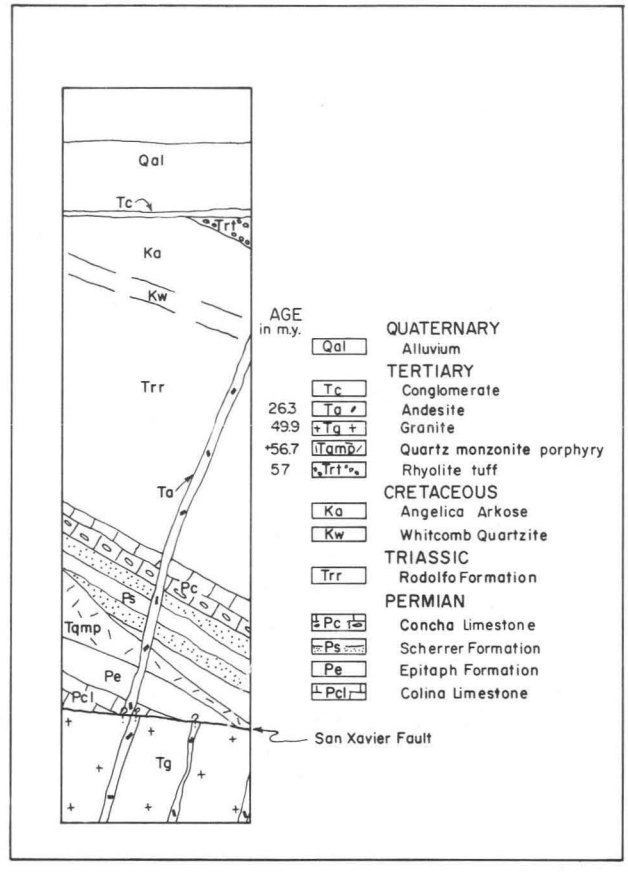

Fig. 2. Generalized stratigraphic section at the Cyprus Pima mine

Stratigraphy

Lithologic complexity and variety characterize the Cyprus Pima deposit. Altered rocks of sedimentary and igneous origin ranging in age from Paleozoic to Tertiary are related to the orebodies. Recognition of formations, especially within the Paleozoic section, is complicated by indistinct lithologic boundaries, subsequent alteration, and intense faulting. A generalized stratigraphic section for Cyprus Pima mine is present in Figure 2.

The oldest rocks present within the pit vicinity are of Permian age. Although the Permian section is intensely altered and recrystallized and all fossil remains are obliterated, the section consists of some of the dominantly marine carbonate members of the Pennsylvanian-Permian Naco Group of southern Arizona. Based on lithologic characteristics, the altered rocks in the pit vicinity belong to the Colina Limestone, Epitaph Formation, Scherer Formation, and Concha Limestone members of the Naco Group. According to Kinnison and Barter (1976), the minimum aggregate thickness of these units in the Pima district is 1,600 feet. Contacts between and within formations are commonly represented by faults of varying attitude and displacement. Based on geologic mapping at the Mission mine, the Permian sequence is in reverse lithologic order (Jansen, 1976). Mineralization, when present in the altered carbonate lithologies, is best developed in the Concha Limestone and the Epitaph Formation. Thickness of the Permian rocks within the pit vicinity is variable, up to 600 to 700 feet.

Mesozoic rocks within the pit vicinity consist of continental to subaqueous clastic sedimentary rocks of Triassic and Cretaceous age (Cooper, 1971). In the type section for the Triassic Rodolfo Formation, the lithologies include red beds, siltstone, and volcanic members with a thickness in excess of 2,400 feet. In the mine vicinity approximately 1,000 feet of possible Rodolfo Formation is present. This formation, as subdivided in the pit by Himes (1973), consists of argillite, arkose, and lithic arenite. The unit is generally massively bedded and probably correlates with the middle siltstone member of the Rodolfo Formation of Cooper (1971). Contacts of the Rodolfo Formation with overlying Cretaceous rocks are diffuse and gradational. However, the lower contact between Permian carbonate rocks and

the Rodolfo Formation appears in part to be a low-angle fault of unknown displacement developed along an unconformity.

Cretaceous units within the mine vicinity may include both the Whitcomb Quartzite and the Angelica Arkose of Cooper (1971). In the type area the Whitcomb Quartzite consists of 300-600 feet of quartz arenite and rhyolitic tuff. Such a lithologic sequence is not at present recognized within the pit vicinity.

The Angelica Arkose in the type locality comprises over 5,500 feet of volcaniclastic, siltstone, sandstone, arkose, and conglomerate lithologies (Cooper, 1971). In the mine vicinity interbedded sections of arkose, subarkose, lithic arenite, and siltstone exposed along upper benches of the south and east walls of the pit are correlated with the Angelica Arkose with the thickness of these units up to 400 feet. Contacts of the Angelica Arkose with lower units are gradational and diffuse.

In terms of importance to mineralization, the Mesozoic rocks are volumetrically the major host and in particular the Rodolfo Formation currently supplies the bulk of the ore tonnage mined. With an 0.03% Cu cutoff grade, 75 percent of the total volume of ore-grade material mined is produced from Mesozoic rocks.

Tertiary rocks in the mine vicinity include a rhyolite tuff, quartz monzonite porphyry, granite, and an andesite. K-Ar age data for some of these rocks are reported in Table 1 (Shafiqullah, 1976). The rhyolitic tuff, also referred to as biotite rhyolite, is mapped by Cooper (1973) just beyond the southeastern fringe of the pit limit. The contact with underlying Angelica Arkose is gradational and may in part be intermixed with arkosic to volcaniclastic sections of the Angelica Arkose. As recognized in drill core to the southeast of the pit limit, the tuff consists of shards and xenocrysts in a variable matrix at least in part of volcaniclastic origin. Sulfide mineralization in the form of pyrite is present as disseminations and veinlets in the tuff. A K-Ar analysis on biotite from a tuff sample located about one mile south of the mine yielded a date of 57 m.y. (Creasey and Kistler, 1962).

The quartz monzonite porphyry exposed within the pit is an altered, sill-like mass that thickens to the northwest. Phenocrysts of biotite, plagioclase, quartz, and rare K-feldspar are set in a xenomorphic matrix of quartz and feldspar. Most contacts of the porphyry are faulted and the present sill-like configuration of the porphyry may be controlled by low-angle faults at upper and lower contacts. Beneath the southwestern section of the pit the porphyry is separated from a younger granite by a low-angle fault zone correlated with the San Xavier fault. Sulfide mineralization in terms of veinlets and disseminations dominated by pyrite is scattered throughout the porphyry. An age date of 56.7 m.y. was obtained from sericite in crosscutting quartz-sericite-pyrite veins in the porphyry (Table 1) (Shafiqullah, 1976).

The porphyry intrusion at the Cyprus Pima mine may be related to late-stage differentiates of the Laramide Ruby Star granodiorite batholith exposed to the south and west of the mine in the core of the Sierrita Mountains. The 58-60 m.y. age of the batholith, as reported by Creasey and Kistler (1962) and Damon and Mauger (1966), is close to the age of alteration of the porphyry from this report. In addition, the similar age of the rhyolite tuff to the granodiorite may indicate a genetic relation to the Ruby Star batholith.

Below the Cyprus Pima pit is a granite of Tertiary age separated from upper-plate lithologies of Paleozoic, Mesozoic, and Tertiary rocks by a low-angle fault correlated with the San Xavier structure of Cooper (1960). This granite is a medium- to coarse-grained, microcline granite that is weakly propylitized. Mineralization in this granite is extremely sparse with scattered grains of pyrite, chalcopyrite, and molybdenite with metal values averaging less than a hundred parts per million. A K-Ar age date on a biotite concentrate from the granite yielded a date of 49.9 m.y. (Shafiqullah, 1976).

Diamond drilling along the northeast corner of the pit has encountered a series of biotite andesite dikes. A generalized log for one drillhole intersection of these dikes is shown in Figure 3. The andesite dike is postmineralization in age, and from Figure 3 it may be seen that the dike is cut by a fault zone correlated with the San Xavier fault. Because of the age relationship between the fault and the dike, a biotite separate was obtained from the andesite and a K-Ar date of 26.3 m.y. was obtained (Shafiqullah, 1976). However, the amount of displacement of the dike along the fault was indeterminate.

Covering the Cyprus Pima deposit to a thickness of as much as 250 feet is a sequence of gravels of possible Pliocene-Pleistocene age (Kelly, 1976). A calcite-cemented conglomerate up to 40 feet thick is commonly found above the bedrock surface and at the base of the unconsolidated gravels. The alluvium and conglomerate were deposited on an oxidized bedrock surface.

Table 1. K-Ar ages of rocks from the Cyprus Pima mine

Sample No.	Description and Location	Material Dated	K%	Radiogenic $^{40}Ar \times 10^{-10}$ mole/gm	Percent Atmospheric ^{40}Ar	Calculated Age in m.y.[1]
UAKA-74-89	Porphyritic biotite andesite from drill core hole A414 at Cyprus Pima mine; lat 31°59', long 111°04', Twin Buttes quad., Pima Co., Ariz.	biotite, slightly chloritized	6.91	316.1 319.6	7.91 7.16	26.3 ± 0.6
UAKA-75-116	Biotite granite from drill core hole A180 at Cyprus Pima mine. Sample taken 500' below San Xavier fault surface; lat 31°59', long 111°04' Twin Buttes quad., Pima Co., Ariz.	biotite, slightly chloritized	7.37	653.4 640.2	8.2 8.2	49.9 ± 1.0
UAKA-75-118	Composite sample of coarse sericite muscovite alteration envelopes cutting quartz monzonite porphyry at Cyprus Pima mine on 2710 bench; lat 31°59', long 111°04', Twin Buttes quad., Pima Co., Ariz.	sericite-muscovite	8.41	847.7 833.9	4.8 5.2	56.7 ± 1.2

[1] Constants: $\lambda_e = 0.575 \times 10^{-10}\ yr^{-1}$, $\lambda_\beta = 4.905 \times 10^{-10}\ yr^{-1}$, $^{40}K/K = 1.18 \times 10^{-4}\ g^{40}K/gK$

Structure

Structural development of the Pima mining district in general and the Cyprus Pima deposit has been complex and varied. The structural complexity of a portion of the district from the Twin Buttes mine to the Cyprus Pima mine is illustrated in Figure 4.

Lacy (1959) recognized various periods of structural development in the district. The older premineralization structural features included folding, steep left-lateral faulting, normal faulting, and low-angle "thrust" faulting. Drewes (1976) also recognized on a regional basis in southern Arizona early premineralization thrust faults and indicated that the thrust development was most active about 75-80 m.y. ago.

Lacy also recognized another period of postmineralization "thrusting" involving the Oligocene Helmet Fanglomerate and andesite dikes. This later period of low-angle faulting is correlative with the San Xavier fault of Cooper (1960). In the Pima mining district, Cooper has proposed that the San Xavier "thrust" fault (or gravity glide fault, Drewes, 1976) was of postmineralization age but pre-andesite dike swarm age (24-26 m.y.) and that the fault had a displacement of about 10 km in a north-northwest direction. Cooper (1971) also suggested that the Cyprus Pima-Mission mines are the displaced upper portions of the Twin Buttes copper deposit located about 10 km to the south.

A generalized geological section from the Twin Buttes area to the Cyprus Pima mine area is presented in Figure 5, adapted from Cooper (1973), Kelly (1976), Weaver (1971), and diamond-drill information. The age of 56.7 m.y. for the sericitic alteration establishes a Laramide age for mineralization and is very close to an age of 57.1 m.y. obtained from the quartz monzonite porphyry at the Twin Buttes deposit (Kelly, 1976). A 49.9-m.y. age for the granite beneath the San Xavier fault requires an age of fault development younger than the granite and the mineralization. Cooper (1960) also concluded that the age of movement along the fault was younger

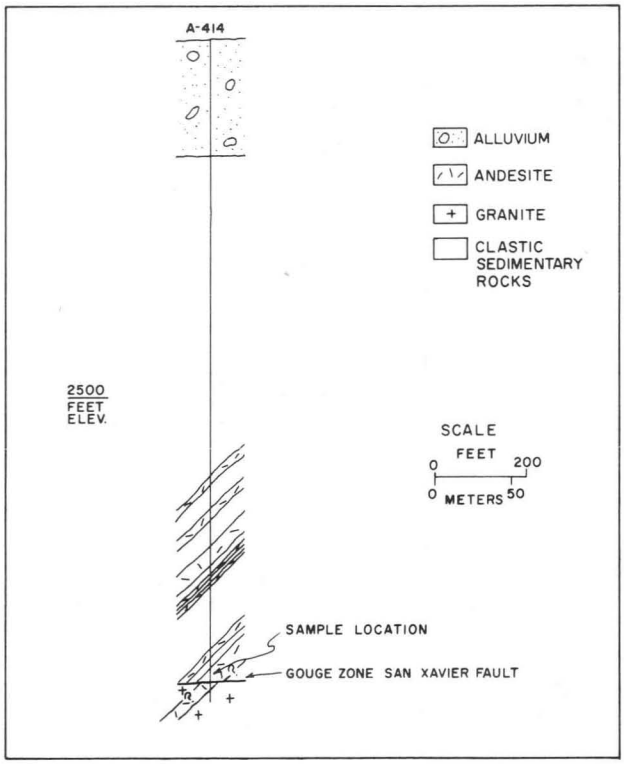

Fig. 3. Generalized log of diamond drill hole showing San Xavier fault cutting andesite dikes

than the Oligocene Helmet Fanglomerate. Because the San Xavier fault cuts a 26.3-m.y. andesite dike in the mine area, at least some of the movement along the fault is younger than the andesite dike event. Therefore, the age of movement along the San Xavier structure is interpreted to be postmineralization and probably extended through late Oligocene to early Miocene time.

Within the pit vicinity the attitude of the Paleozoic and Mesozoic sedimentary rocks varies from N. 60°-75° E. with dips ranging from 45°-65° SW. (Dames and Moore, 1976). Detailed structural data related to orientation of faulting and jointing were collected by Himes (1973) and Dames and Moore (1976). Two major directions of faulting were found: N. 50°-60° E. and N. 40°-50° W. These data are compatible with the principal Laramide trends as reported by Rehrig and Heidrick (1972). Dames and Moore (1976) also noted an additional major fault attitude of N. 10°-20° W. According to Rehrig and Heidrick (1976) this direction corresponds to late Terriary structural trends.

Measured joint patterns are much more variable. The east-northeast and the northwest strike directions for joints again are compatible with Laramide trends. Attitudes of N. 0°-20° W. for joints correspond to late Tertiary structural directions. Other joint orientations, such as N. 12° E. as reported by Himes (1973), are of uncertain age and origin.

Figure 6 presents a generalized geologic map at the 2670 elevation, and Figure 7 shows a generalized contour map of the San Xavier fault surface in the mine vicinity. From the contour map the gentle eastward-dipping slope of the fault surface is interrupted by a north-northwest depression in the contours. This depression may be a result of a graben structure or a large mullion structure (Jansen, 1976) related to the San Xavier fault. Figure 7 also shows the location of sections through the Cyprus Pima mine.

Figure 8 shows a northwest-southeast section oriented oblique to the depression in the San Xavier fault surface. From the section high-angle and low-angle structures of various ages may be noted. The generalized sill-like nature of the porphyry intrusion may also be noted. On this section the San Xavier fault, which separates Tertiary granite from altered Paleozoic carbonate rocks, is the youngest structure.

Figure 9 is a northeast-southwest section oriented across the contour depression of the San Xavier fault surface. As in the previous section early high-angle structures are displaced by the San Xavier fault. Other high-angle structures younger than the San Xavier fault have displaced the surface of the fault by hundreds of feet. The eastern edge of the contour depression of the San Xavier fault may be caused by a series of steep en echelon faults as shown on the section, although the possibility of a mullion structure cannot be eliminated.

Alteration

Alteration patterns of the igneous and clastic sedimentary rocks at Cyprus Pima mine are similar to the general mineral assemblages and distributions as reported by Lowell and Guilbert (1970) for other porphyry copper deposits. However, alteration of the Paleozoic marine carbonate sequence by presumably similar pressure-temperature solution composition variables has produced assemblages consisting of garnet, diopside, tremolite, and other Ca-Mg silicates.

The Mesozoic clastic section and the quartz monzonite porphyry show abundant evidence of potassic and, to a lesser extent, sericitic alteration (Himes, 1973). Secondary K-feldspar as alteration halos and as massive wall-rock replacement is common in the clastic

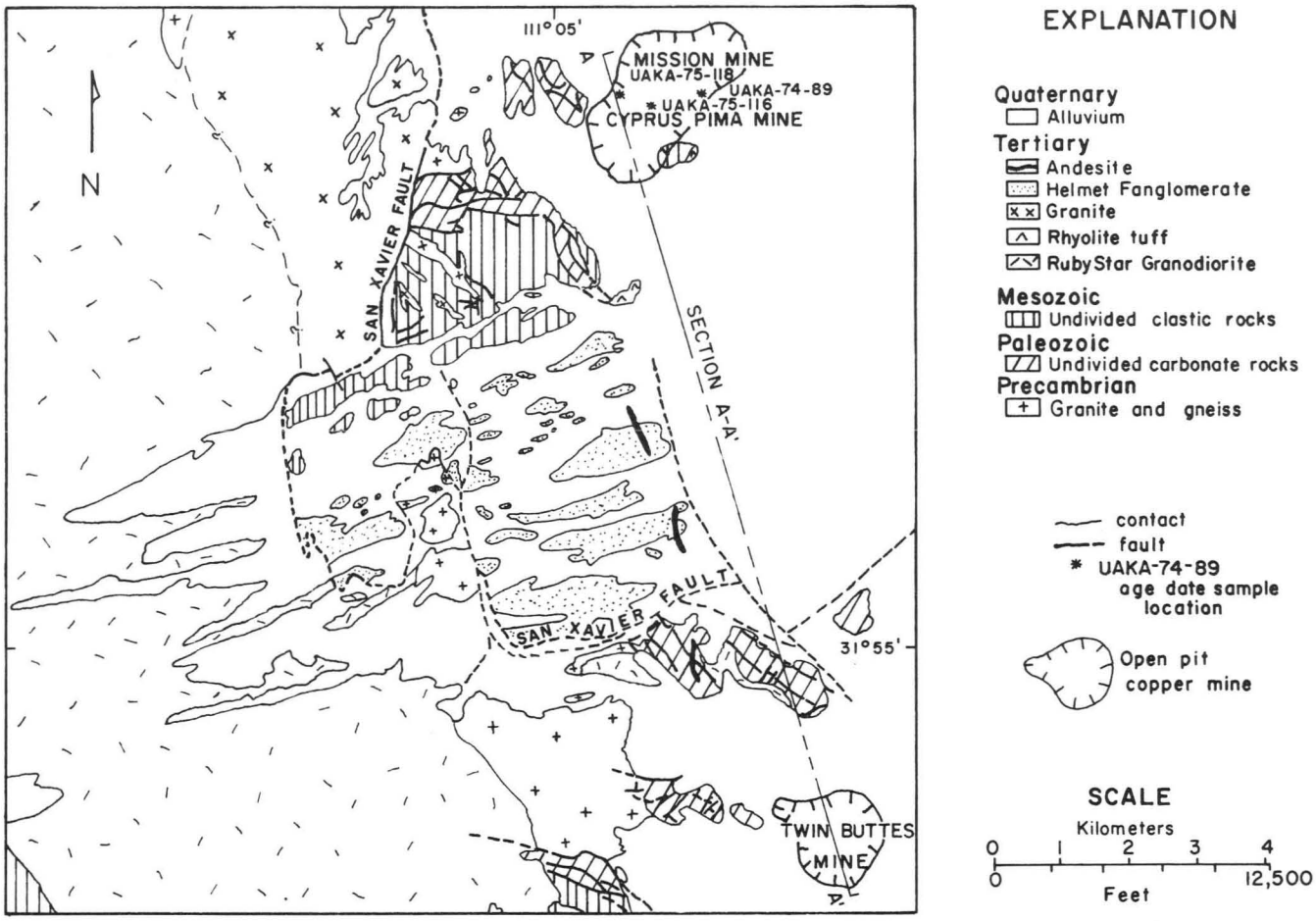

Fig. 4. Generalized geologic map of a portion of the Pima mining district extending from the Cyprus Pima mine to the Twin Buttes mine—adapted from Cooper (1973)

sedimentary rocks and the quartz monzonite porphyry. Common associates of this assemblage are sericite, calcite, anhydrite, and sulfides.

Sericitic or phyllic alteration is generally restricted to vein alteration halos ranging from 1 to 5 cm wide. The alteration assemblage is characterized by feldspar-destructive quartz, sericite-muscovite, and sulfides with the sericitic veins and alteration halos crosscutting the potassic alteration mineral assemblages in the quartz monzonite porphyry. Development of the sericitic alteration is best in the quartz monzonite porphyry along the western face of the pit wall. A more diffuse and less distinct zone of sericitic alteration may be present on the upper benches of the east pit wall in the Mesozoic clastic sedimentary rocks.

Propylitic alteration assemblages as recognized by Himes (1973) are generally restricted to the southwestern part of the pit. An assemblage of epidote, chlorite, calcite, quartz, and sericite is present in Mesozoic clastic rocks together with scattered quantities of sulfides.

Alteration of the Permian carbonate section has produced various types of calcium silicate hornfels and tactites. Pyrometasomatism and recrystallization combined with hydrothermal alteration have resulted in hornfels composed of andradite or grossularite garnet, diopside, tremolite, magnetite, calcite, quartz, and biotite. The distribution of the different types of hornfels is variable and probably reflects initial differences in composition of different facies of impure carbonate lithologies. Sulfides are distributed in the hornfels as local massive clots and in and adjacent to veins.

Crosscutting the tactite sections are veins with associated alteration halos of actinolite, epidote, magnetite, and serpentine. This later stage alteration event may be related to the crosscutting sericitic alteration that developed in the igneous and clastic rocks.

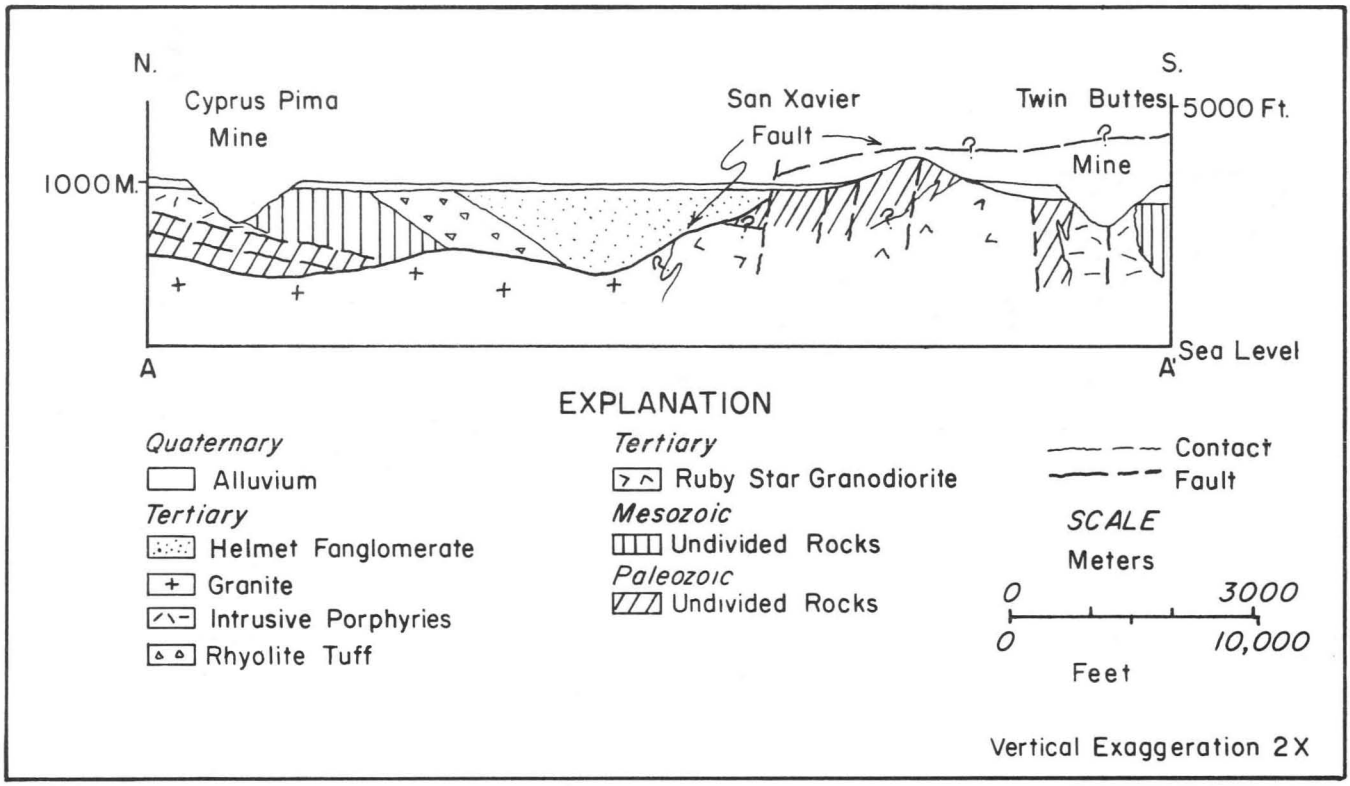

Fig. 5. Geologic section from Cyprus Pima mine to the Twin Buttes mine

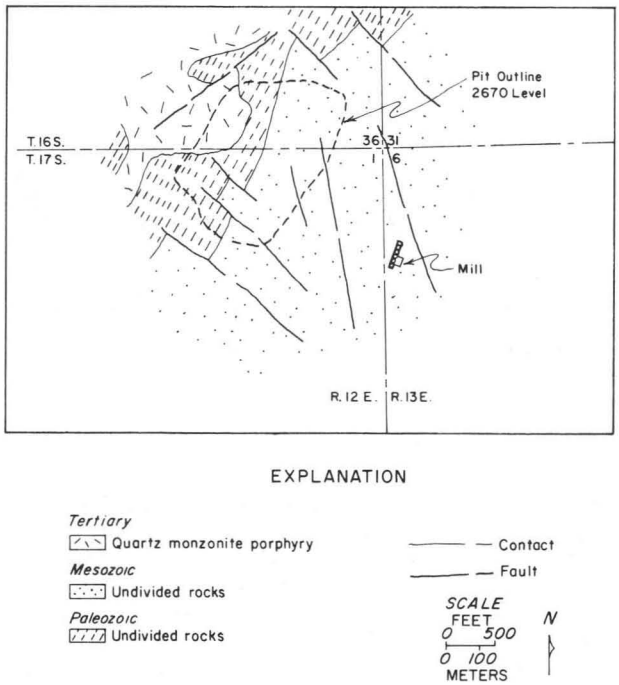

Fig. 6. Geologic map at the 2670 elevation

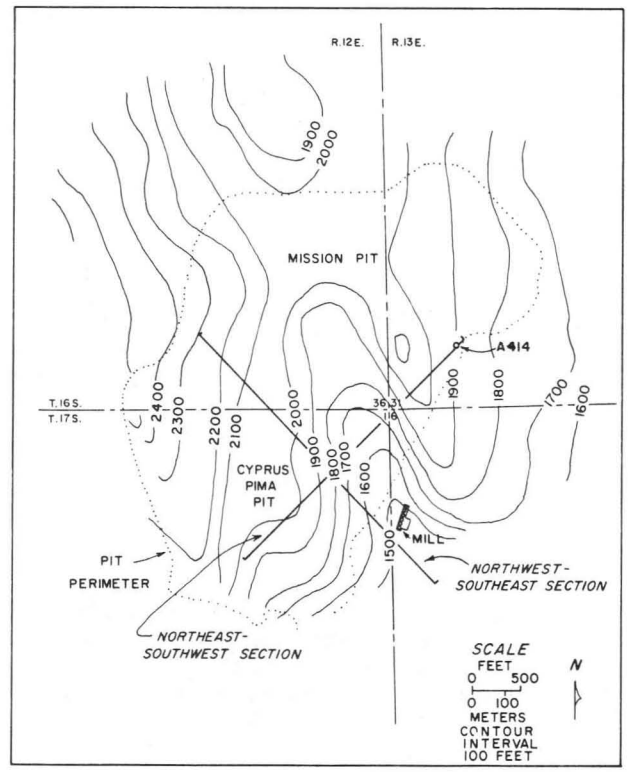

Fig. 7. Generalized contour map of San Xavier fault surface based on data from the Cyprus Pima and Mission mines

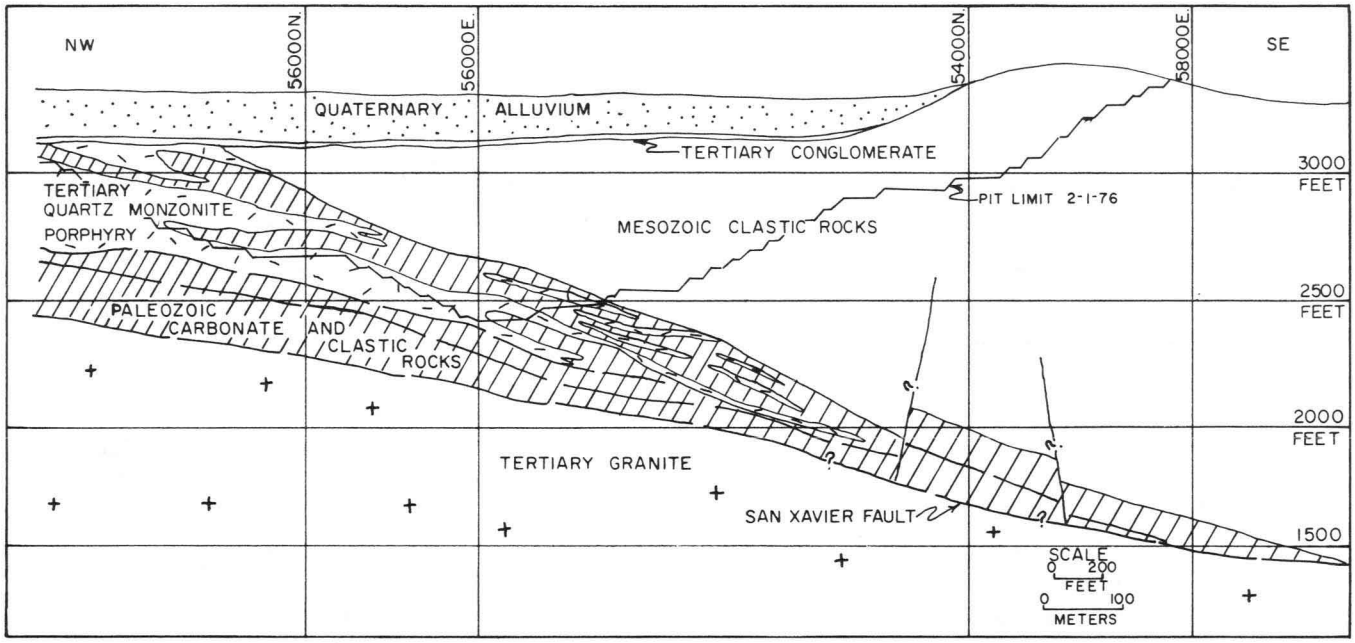

Fig. 8. Northwest-southeast cross section through the Cyprus Pima mine

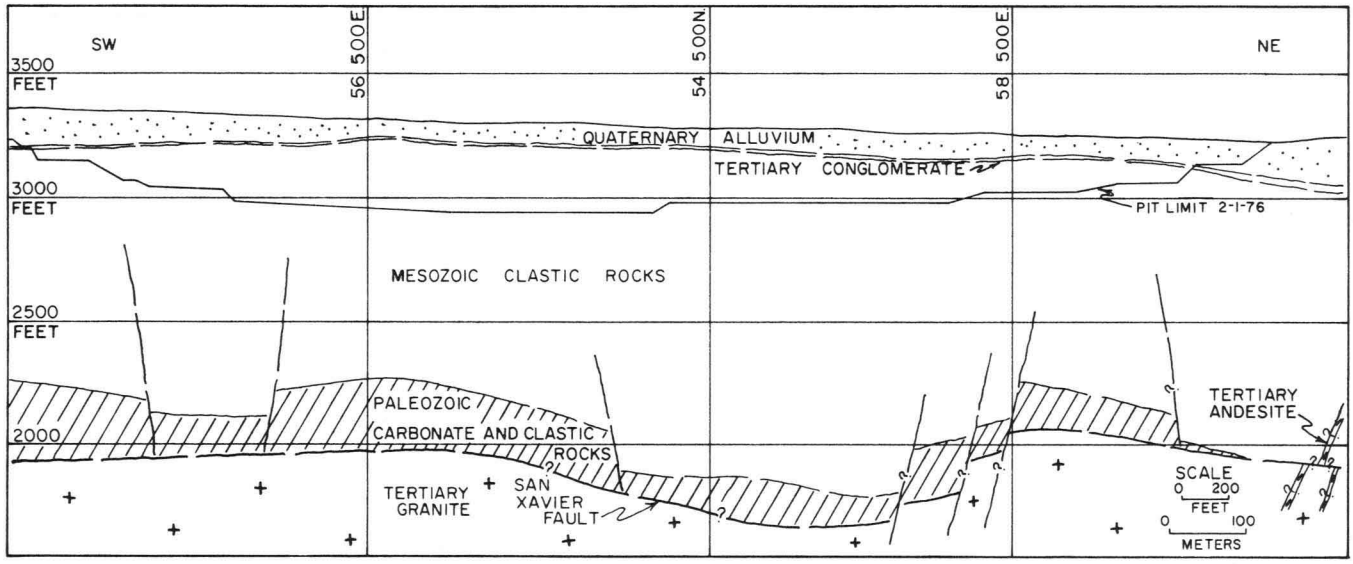

Fig. 9. Northeast-southwest cross section through the Cyprus Pima mine

Supergene alteration effects are largely limited to the development of clay minerals, iron oxides, copper oxides, and sparse chalcocite along upper benches of the pit. Gypsum and calcite are also present as fracture fillings deep within the pit. Alunite of uncertain origin and mixed with clay minerals occurs as fracture fillings along the highest benches of the southeast margin of the pit.

Mineralization

Sulfide mineralization in the Cyprus Pima orebody consists of veinlet, disseminated, and locally massive types with chalcopyrite the dominant copper sulfide. Veinlet and disseminated types in approximately equal proportions are most abundant in the altered Mesozoic clastic sections and massive replacement type sulfide mineralization is largely limited to the altered Paleozoic carbonate lithologies.

Other common sulfide minerals include pyrite and molybdenite with lesser amounts of sphalerite, galena, tennantite-tetrahedrite, chalcocite, bornite, and valleriite. Local massive occurrences of sphalerite, magnetite, and chalcopyrite are limited to tactite bodies present in the western part of the mine. Chalcocite is present only in limited quantities and in small tonnages relative to total reserves near the relatively shallow base of oxidation. According to Parkinson (1976), current average ore grades are 0.47% Cu and 0.015% Mo. Silver is also recovered as a by-product from the ores during the smelting process.

Structural and lithologic controls are important to ore distribution at Cyprus Pima mine. Preore brecciation and stockwork fracturing were the major ore controls. Wall-rock environment as controlled by lithologies also played a major role in sulfide distribution. Table 2 summarizes grade distribution data for each lithologic type based on grade distributions for bench level averages. Assuming that each of the lithologies was subjected to the same structural environment and channelways, the relative order for each lithology as a copper sulfide host based on the statistics is

Table 2. Copper-grade distribution data for bench-level averages from diamond drill holes for various lithologic types

Lithology	Median Grade [1]	Arithmetic Average of Grades	Total Number of Data Points
Paleozoic tactite and hornfels	0.62	0.81	360
Mesozoic clastic rocks	0.33	0.38	1459
Paleozoic quartzite and clastics	0.20	0.23	131
Tertiary quartz monzonite porphyry	0.12	0.15	177
Paleozoic marble and limestone	0.03	0.11	94

[1] 50% cumulative frequency

Paleozoic hornfels, Mesozoic clastic rocks, Paleozoic quartzite, Tertiary porphyry, and Paleozoic limestone.

Figures 10 and 11 show grade distributions based on a 40-foot running average contouring system for the Cyprus Pima deposit. Postmineralization displacement of orebodies is illustrated by these sections. Low-angle structures complementary to the San Xavier fault truncate hornfels ore sections below the porphyry body and hundreds of feet above the San Xavier fault in the northern portions of both sections. The sections also illustrate the relative potential of the Mesozoic clastic section, Paleozoic hornfels, and Tertiary porphyry as orebody hosts.

Molybdenite mineralization, although processed in the milling operation, shows a poor correlation with copper content. Figure 12 graphically illustrates the lack of correlation and a statistically derived correlation coefficient of 0.378 confirms this observation. Inspection of molybdenite occurrences in the mine suggests that molybdenite distribution increases in silica-rich rocks, such as the porphyry and certain clastic units.

Zoning relationships at the Cyprus Pima mine are poorly known. With increasing distance to the east away from the present location of the porphyry, the proportions of tetrahedrite-tennantite and sphalerite to chalcopyrite increase. Bornite occurrence relative to chalcopyrite is highest in slightly marbleized sections below the main ore zone.

Oxide minerals at the Cyprus Pima mine include chrysocolla, tenorite, malachite, and azurite. Because of the relatively small quantities of oxide copper minerals present, oxide ores are not processed.

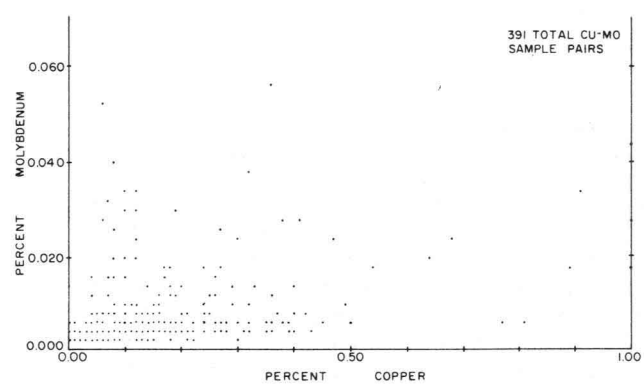

Fig. 12. Plot of corresponding copper and molybdenum bench averages from drill-hole data

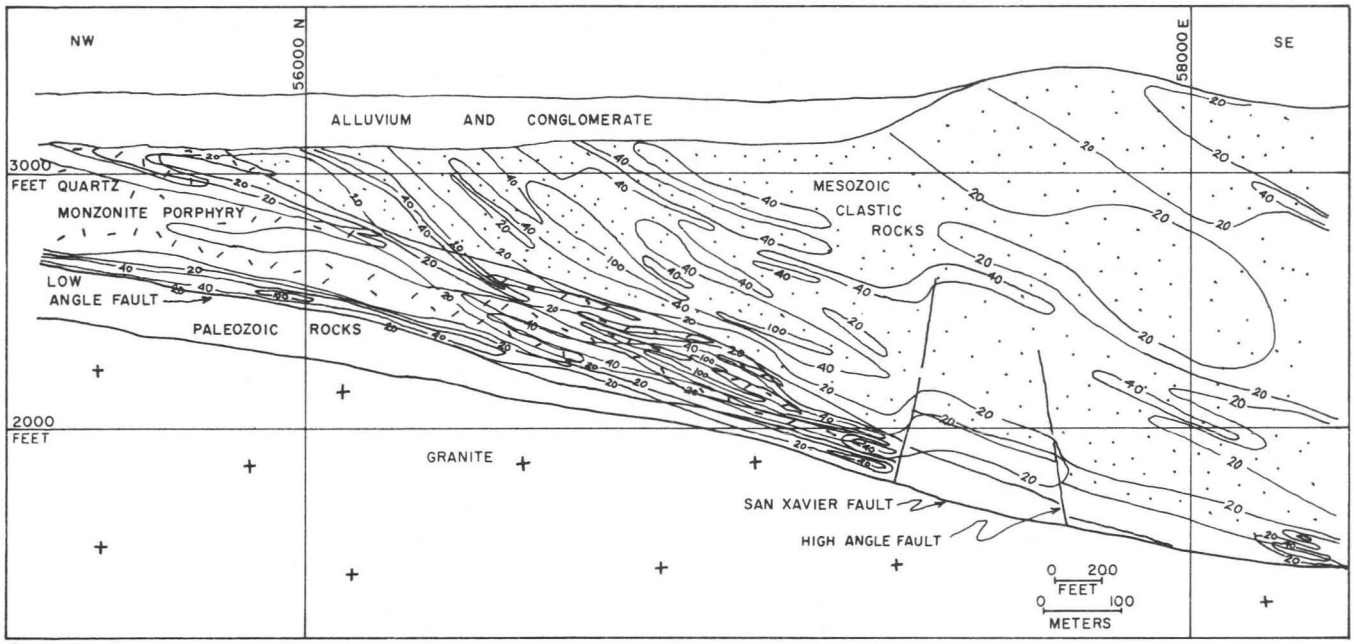

Fig. 10. Grade contour section based on 40-foot running averages for a northwest-southeast section through the Cyprus Pima mine

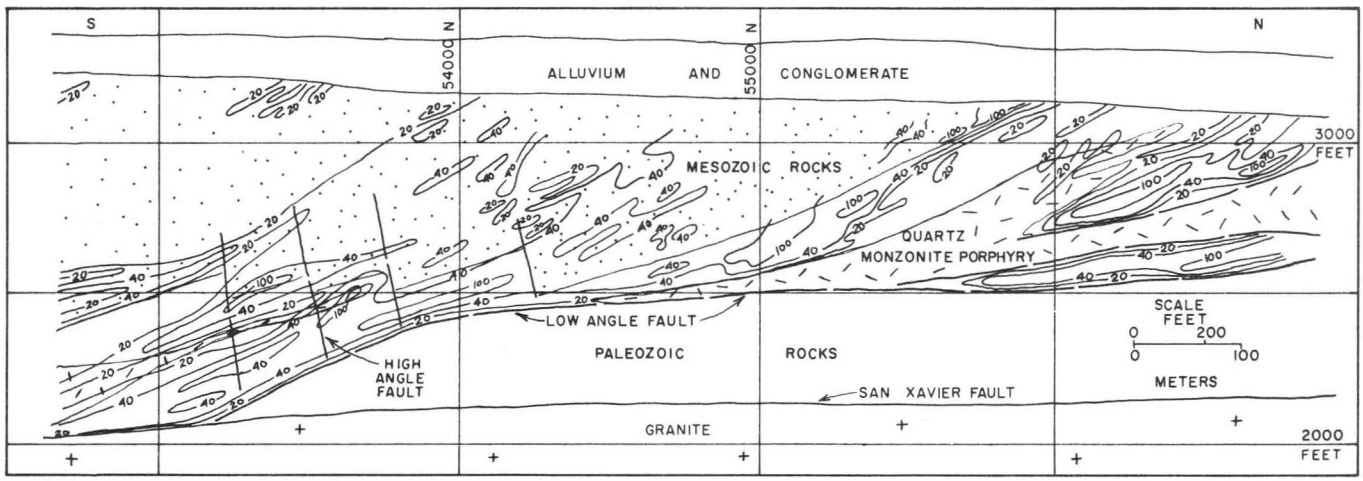

Fig. 11. Grade contour section based on 40-foot running averages for a north-south section through the Cyprus Pima mine

Himes (1973) regards the alteration-mineralization processes at the Cyprus Pima mine as contemporaneous with and related to the emplacement of the quartz monzonite porphyry. Although sulfides appear to preferentially replace calc-magnesian silicates in tactite zones, the alteration-mineralization events probably developed over a continuum of pressure-temperature conditions. Early high-temperature conditions resulted in development of tactite, some K-silicate alteration, and some sulfides. Lower temperature conditions resulted in actinolite, magnetite, and sericitic alteration developed in conjunction with dominantly pyritic sulfides. The present distribution of sulfide ore horizons was a function of premineralization fracturing and favorable lithologic environments and of postmineralization displacement along low-angle fault planes.

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STRATIGRAPHY, ALTERATION, AND ORE CONTROLS IN THE MAIN ORE ZONE, TWIN BUTTES MINE, PIMA COUNTY, ARIZONA

by

Charles F. Barter

Abstract

The Twin Buttes and Sierrita-Esperanza deposits are located at the two known mineralization centers on the eastern side of the Sierrita Mountains. Both centers are characterized by plugs and dikes of quartz monzonite porphyry intruded along the southern and southeastern flank of a Laramide granodiorite batholith.

At Twin Buttes, a southeast-trending, elongate mass of quartz monzonite with a variety of related porphyries extends from the batholith and intrudes the Paleozoic and Mesozoic sequences. A thermal and metasomatic aureole has been formed around this intrusive complex. The Paleozoic through Laramide rocks are covered by 300 to 600 feet of gravels; the lower portion of which is of probable Pliocene age. The Twin Buttes deposit is segmented by postmineralization, northeast-trending normal faults and low-grade intrusions. The main ore zone is located on the southwest side of a quartz monzonite porphyry mass dated at 58 m.y.

The Mesozoic sequence in the main ore zone is folded into an open syncline. At the top of this sequence is the two-member Angelica Arkose. The Angelica is underlain by volcanics and clastics of Triassic and possible Jurassic age. An angular unconformity separates Triassic from younger Mesozoic rocks. At the base of the Mesozoic is a carbonate-rich conglomerate which overlies the Paleozoics along a 50° SW.-dipping angular unconformity.

The Paleozoics generally have steep northeast dips and are strongly folded. The youngest, northernmost, Paleozoic in the main ore zone is the Permian Concha Limestone and the oldest is the Earp Formation. Between these formations are a three-member Scherrer Formation, a four-member Epitaph Formation, and the Colina Limestone.

Alteration in the Mesozoic clastics and volcanics consists of partial recrystallization, biotization, and later sericitization developed most strongly along quartz-sulfide veinlets. In these rocks, there is a general decrease in biotite and an increase in epidote and pyrite away from the intrusion. Only the Angelica Arkose contains persistent unenriched grades above 0.4 percent copper.

Early skarn formation in the Paleozoic carbonates involved extensive magnesium metasomatism. Diopside, pale garnet, and local wollastonite were among the first alteration minerals developed. A later stage of darker garnet with associated chalcopyrite-rich sulfides replaced and veined the earlier calc-silicates. Subsequently, the earlier skarns were partially altered to hydrous calc-silicates, such as tremolite, actinolite, and nontronite, adjacent to pyrite, chalcopyrite, quartz, anhydrite stringers and near the relatively permeable siltstones. Hypogene alteration-mineralization essentially ended with the introduction of quartz-pyrite veins containing some sphalerite, chalcopyrite, and galena and minor amounts of fluorite and tetrahedrite. Increased amounts of partially silicated marbles is the most obvious manifestation of decreasing metasomatism in the Paleozoic carbonates.

In the quartzose clastics of the Paleozoic section, early alteration consists of partial recrystallization, biotization, and formation of diopside in calcareous siltstones and

[1] Anamax Mining Company, Sahuarita, Arizona 85629

quartzites. Later alteration of diopside to hydrous calc-silicates and alteration of biotite to sericite occurs along quartz, anhydrite, sulfide veinlets, and in varying degrees throughout particular siltstone horizons.

The single most important ore control at Twin Buttes is the altered carbonate rocks. Superimposed on this dominant feature are factors such as distance from the mineralization center, proximity to permeable rocks, intensity of fracturing, and partial reworking of early sulfides by later hydrothermal events.

An understanding of these controls and careful documentation of their effects allowed postulation of a high-grade reserve in the main ore zone. Subsequent drilling has proved the presence of a number of strata-limited ore bands containing a significant tonnage of high-grade mineralization.

SOME GEOLOGIC ASPECTS OF THE SIERRITA-ESPERANZA COPPER-MOLYBDENUM DEPOSIT, PIMA COUNTY, ARIZONA

by

Daniel M. Aiken[1] and Richard J. West[2]

Abstract

The Esperanza property, which had been worked sporadically since 1895, was purchased by Duval Corporation in 1955. Following completion of an exploration drilling program under the direction of Harrison Schmitt, pre-mine stripping started in 1957 and subsequent production started in 1959. With the beginning of stripping in early 1968 and the start of mill operations in March 1970, the Sierrita mine became one of the largest copper-molybdenum ventures in Arizona. The combined Sierrita-Esperanza complex will eventually be a pit 12,500 feet long, 6,500 feet wide, and 2,250 feet deep.

The Sierrita and Esperanza properties constitute a porphyry-type copper-molybdenum deposit which occurs within intensely fractured and moderately altered rhyolite and andesite, quartz diorite, dacite porphyry, quartz monzonite, and quartz monzonite porphyry with an attendant intrusive breccia. Essential to the emplacement of the orebody is the Laramide Ruby Star granodiorite from which ore solutions were derived. The deposit lies at the south end of this pluton, which makes up much of the Sierrita Mountains.

Alteration in the ore zone is predominantly potassic, with phyllic and minor argillic assemblages. Propylitic minerals commonly occur outside the pit areas. All rock types are mineralized and altered.

Major primary minerals are limited to pyrite, chalcopyrite, and molybdenite. Silver, although recovered in minor amounts, is not recognized in mineral form. Minor minerals include galena, sphalerite, tennantite-tetrahedrite, magnetite, marcasite, fluorite, and rare bornite. Significant amounts of secondary enrichment were limited to Esperanza and West Esperanza. Initial interest in these two areas was due to the presence of a well-developed chalcocite blanket, most of which has been mined. Other secondary minerals commonly found include cuprite, tenorite, malachite, azurite, chrysocolla, native copper, and minor turquoise.

Mineralization at Sierrita-Esperanza is structurally and lithologically controlled. Linear mineralized zones parallel or girdle fault trends, major joint sets, and intrusive contacts. In addition, hypogene mineralization is associated with specific rock types and is generally fracture controlled within these units. Minor disseminations commonly occur in the breccia and quartz monzonite porphyry.

Introduction

The Duval Sierrita-Esperanza complex is located 25 miles south-southwest of Tucson, Arizona, on the southeast flank of the Sierrita Mountain range. Five miles to the east lies the Twin Buttes deposit and about 12 miles to the northeast, the Pima-Mission orebodies.

The Sierrita and Esperanza deposits were brought into production as separate open pits within parts of a single large mineralized system and are now being integrated into one of the world's largest copper-molybdenum operations.

Mining in the Esperanza area began late in the 19th century as sporadic underground working of relatively high grade base and precious metal veins. The New Years Eve mine (known then as the Red Carbonate mine), located in what is now the Esperanza pit, was partly developed by the Calumet and Arizona Mining Company in 1907-08 and abandoned due to low copper prices. During the 1930s and 1940s several companies examined the New Years Eve

[1,2] Duval-Sierrita Corporation, Sahuarita, Arizona 85629

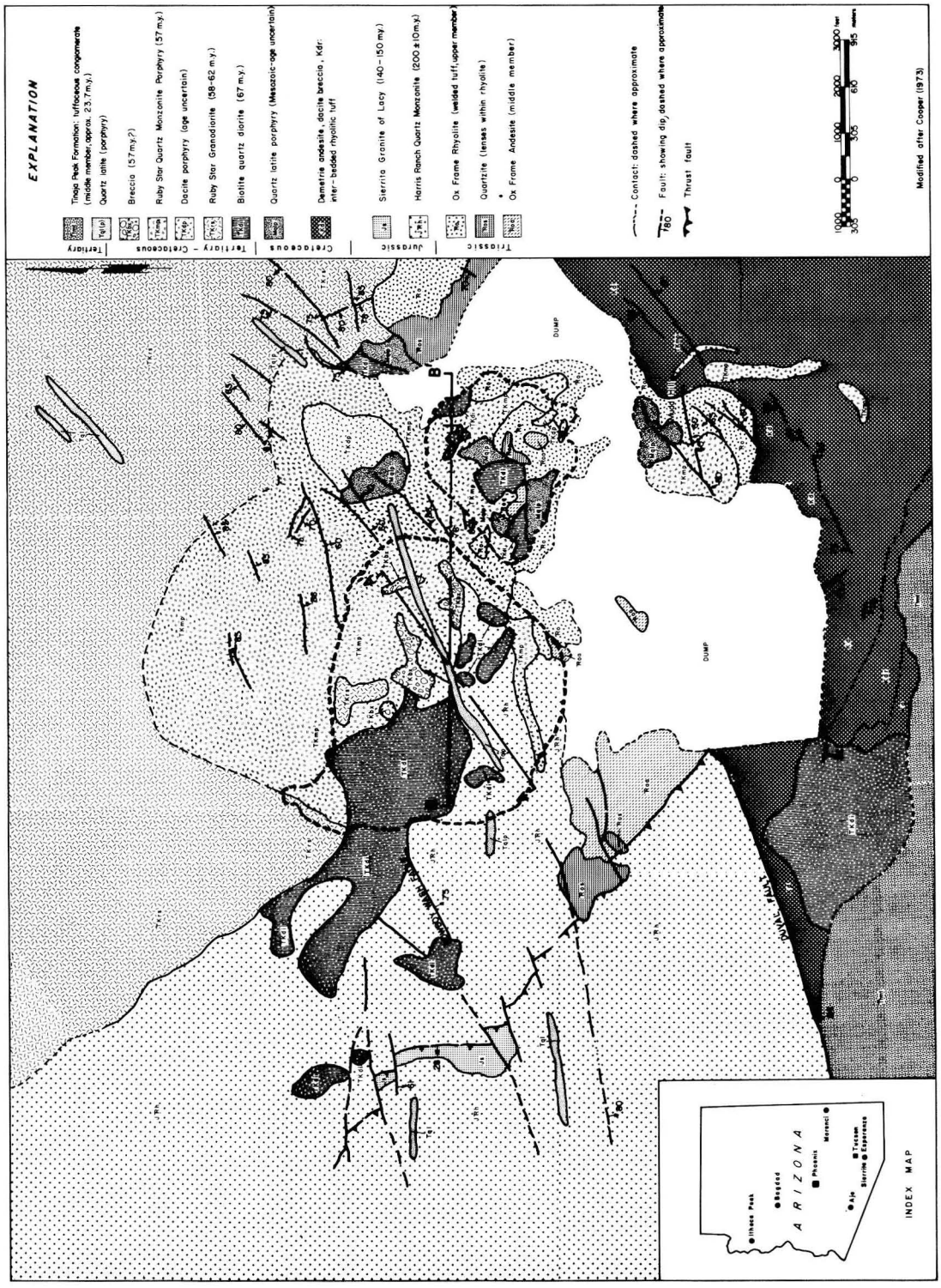

Fig. 1. Geologic map of Sierrita-Esperanza deposit—modified from Cooper (1973)

mine as a potential source for molybdenum. The U.S. Bureau of Mines, seeking new sources of molybdenite against the possible shortage of that mineral for war uses, examined the New Years Eve mine area in 1943 and 1944.

In the early 1950s the Duval Sulphur and Potash Company (later Duval Corporation) began searching for major copper deposits. Harrison A. Schmitt, consulting geologist, was retained to locate possible targets. Following an examination of the Esperanza deposit by Schmitt, Duval acquired the claims in February 1955 from the Sierrita Mining and Ranching Company. A drilling program was initiated and by 1957 had revealed sufficient tonnage to warrant development of an open-pit mine.

Duval was initially attracted to Esperanza by the presence of a well-developed chalcocite blanket, most of which has now been mined out. Pre-mine stripping began in 1957 with production commencing in 1959. The ore grade at Esperanza has averaged 0.5% Cu and 0.028% Mo since the start of operations. Ore reserves for Esperanza are now about 36 million tons with grades of 0.38% Cu and 0.027% Mo (Pennzoil Company, 1974). Current daily production is 18,000 tons ore and 18,000 tons waste.

In 1963 Duval acquired additional properties which comprised approximately 60 percent of the then undeveloped Sierrita orebody. Exploration and development drilling has established total ore reserves of 554 million tons with a grade of 0.32% Cu and 0.033% molybdenum (Pennzoil Company, 1974). Pre-mine stripping began in 1968 with initial production in 1970. Ore mined during the early years at Sierrita has averaged 0.29% Cu and 0.028% Mo. Present daily production is about 90,000 tons ore and 135,000 tons waste.

General Mine Geology

The Sierrita-Esperanza deposit occurs within intensely fractured and moderately altered rhyolitic and andesitic volcanic rocks, quartz diorite, quartz latite porphyry, dacite porphyry, quartz monzonite, and quartz monzonite porphyry, with an attendant intrusive breccia. Except for quartz monzonite, which is restricted to southwest Sierrita, all rock types crop out in both pits.

Rock Types

Table 1 gives a summary of the age and description and occurrence data for rock types in the Sierrita-Esperanza mine area.

Extrusive Rocks

The Ox Frame Volcanics of Triassic age are mainly flows which cover much of the terrain west of Sierrita and comprise the upper levels of the Esperanza pit. The lower member of the Ox Frame does not crop out in the mine area. Subdivisions of the formation present in the mine area consist of:

1. Andesite—the middle member of the extrusive sequence. Typical andesite is dark gray to black and microporphyritic, consisting of 20 to 30 percent plagioclase phenocrysts set in an aphanitic groundmass of albite, actinolite, and magnetite microlites with a cryptocrystalline texture.

2. Rhyolite welded tuff—the upper member of the Ox Frame Volcanics. This dark-gray rock was subdivided by Lynch (1967) into vitric tuff, fragmented tuff, and siliceous-aphanitic tuff based on suble differences in texture, welded characteristics, and microstructure.

3. Quartzite—occurs as isolated pods and irregular masses interbedded with the rhyolite in Esperanza.

Only andesite was an important host for hypogene mineralization. Significant secondary copper enrichment has been restricted to highly fractured zones in all units of the Ox Frame Volcanics.

Intrusive Rocks

Harris Ranch Quartz Monzonite. An extension of the southeast end of the Harris Ranch quartz monzonite stock crops out in southwestern Sierrita (Fig. 1). Diagnostic of this light-gray, medium-grained rock is the biotite, which normally occurs as subhedral flakes in aggregates. Tourmaline is common in the Harris Ranch quartz monzonite above the 3900 level and may be a primary mineral. It diminishes toward the contact with the Laramide intrusions reflecting a chemical change possibly caused by hydrothermal solutions associated with the younger Laramide rocks (Guilbert, 1977, personal communication).

The Harris Ranch quartz monzonite was not originally recognized as an important host for mineralization. The results of deep drilling indicate an extensive hypogene ore zone which begins several hundred feet below the original surface and continues downward into younger Laramide rocks (Fig. 2). The Harris Ranch quartz monzonite, with an age date of 200 $\pm$ 10 m.y., is the oldest intrusive rock in the mine area (Figs. 2 and 3).

Table 1. Extrusive and intrusive rocks in the Sierrita-Esperanza mine area

Name	Age	Description and Occurrence
Quartz latite porphyry	Eocene (?)	Pods and high-angle dikes (weakly mineralized)
Ruby Star quartz monzonite porphyry	Eocene 53.5 m.y. (Damon and associates, 1966) 56 m.y. (Creasey and Kistler, 1962) 56.9 m.y. (Cooper, 1973)	Stocks and plugs (probable source for metal-bearing hydrothermal solutions and an important host for mineralization)
Breccia	Eocene 57 m.y.?	Irregular pipelike bodies; large discontinuous masses; dikes
Dacite porphyry	Eocene-Paleocene	Dikes and irregularly shaped bodies; may be genetically related to quartz monzonite porphyry
Ruby Star granodiorite	Eocene 58.7 m.y. (Damon and associates, 1966) 59 m.y. (Damon and associates, 1965) 61.6 m.y. (Cooper, 1973)	North-northwest-trending batholith considered to be source magma for quartz monzonite porphyry
Biotite quartz diorite	*Paleocene(?) 67.0 m.y. (Cooper, 1973)	Northwest-trending, rectangular stock and smaller bodies (excellent host for mineralization)
Quartz latite porphyry	age uncertain	Irregular plugs and pods within and north of Esperanza mine
Demetrie Volcanics	Late Cretaceous	Sequence of andesitic and dacitic breccias and flows located southeast of Esperanza mine
Sierrita granite	Jurassic 140 m.y. (Damon and associates, 1966) 150 m.y. (Cooper, 1973)	Located west and north of Sierrita-Esperanza
Harris Ranch quartz monzonite	Jurassic-Triassic 190 m.y. 210 m.y. (Cooper, 1973)	Northwest-trending stock (excellent host for mineralization)
Ox Frame Volcanics	Triassic	Rhyolite flows, tuffs, and tuff breccias with intercalated lenticular beds of sandstone; andesite and dacite flows, with a few flow breccias; andesite is a good host for mineralization at Esperanza

*Additional radiometric dates of 47.0, 56.0, and 60.0 m.y. have been obtained from minerals in quartz veinlets in diorite (Cooper, 1973); vein emplacement may be related to Ruby Star granodiorite intrusion.

Quartz Latite Porphyry. The Mesozoic quartz latite porphyry, a light-colored, fine-grained porphyritic rock, intrudes the Ox Frame Volcanics on the southwest side and central part of the Esperanza deposit. North of Esperanza, a similar unit is recognized. The quartz latite porphyry was a favorable host for primary copper and molybdenum and secondary enrichment in the mine. However, because of its limited areal extent, it does not provide an important source of ore. Field relationships indicate that this rock type is younger than the Triassic volcanic rocks but older than the Ruby Star quartz monzonite porphyry.

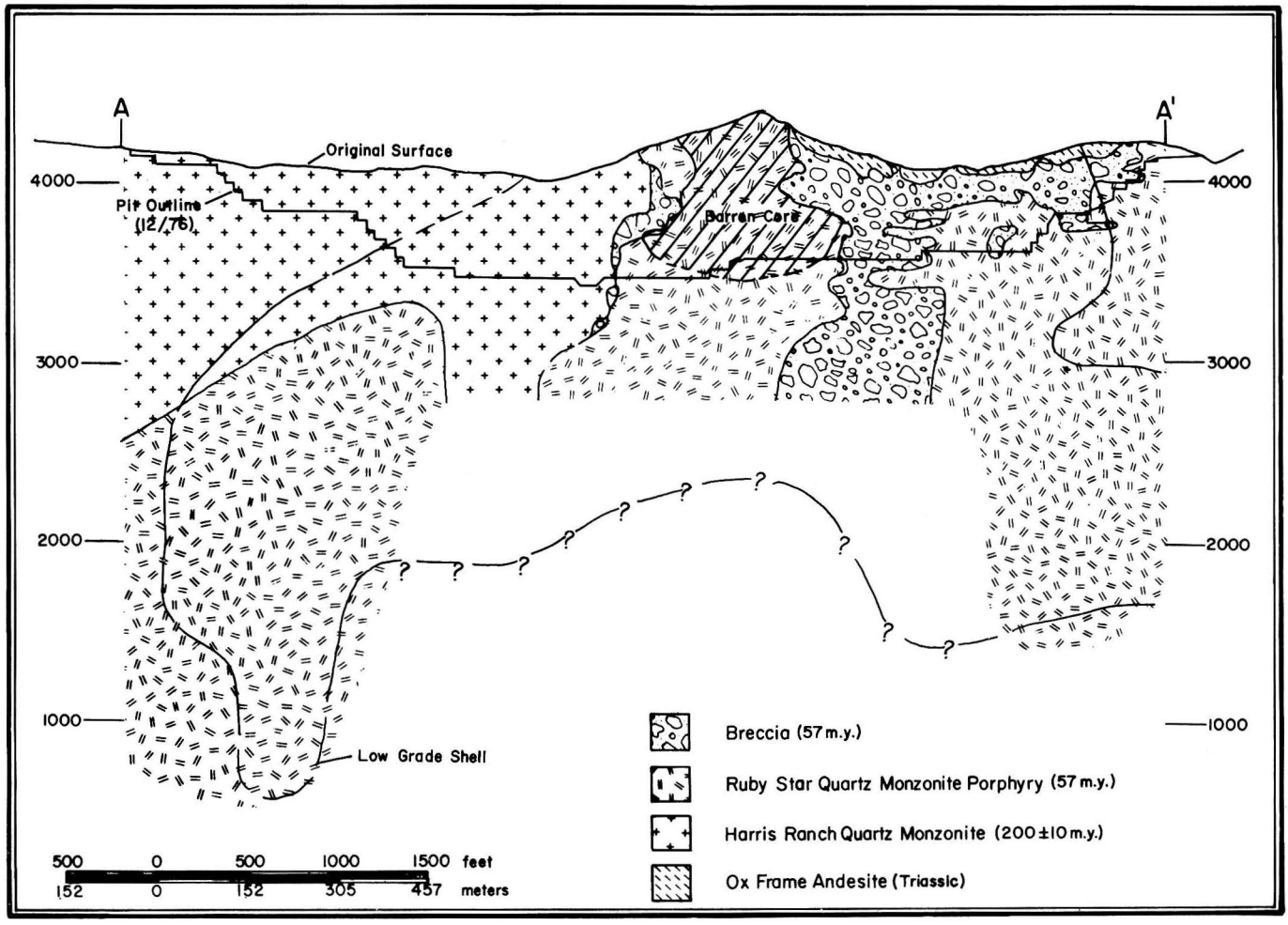

Fig. 2. Section A-A', showing Sierrita geology

Biotite Quartz Diorite. Biotite quartz diorite is found north of Sierrita as irregular plutons and extends into the north end of the mine as a northwest-trending tabular body. The unit is also present in the west and southeast part of Esperanza. In an east-west cross-sectional view of the Sierrita pit (Fig. 4a), the wedge-shaped diorite is intruded by the Ruby Star quartz monzonite porphyry. This dark-green to black, fine- to medium-grained rock commonly exhibits a salt-and-pepper appearance in both weathered and fresh exposures. The diorite is an excellent host for hypogene copper-molybdenum mineralization. Moderate shattering prepared the chemically receptive rock for the invasion of hydrothermal solutions that accompanied the younger Laramide intrusions.

The biotite quartz diorite is Late Cretaceous (Laramide) having an age of approximately 67 m.y.

Ruby Star Granodiorite and Quartz Monzonite Porphyry. Occurring north of the biotite quartz diorite is the Ruby Star granodiorite, a north-northwest-trending batholith with two textural variations and a quartz monzonite porphyry differentiate. The granodiorite in the mine area is a light-gray, medium-grained rock distinguished from other rock types by an abundance of "fresh" equidimensional books of biotite and occasional small, honey-colored crystals of sphene. Mineralization in the granodiorite is sparse, usually occurring as rare chalcopyrite blebs replacing biotite and as copper oxides and carbonates. The several potassium-argon age dates determined for this Laramide intrusive rock average approximately 60 m.y.

The Ruby Star quartz monzonite porphyry, a light-gray, porphyritic facies of the Ruby Star granodiorite, is characterized by anhedral quartz "eyes" which are preserved even in intensely weathered rock. The intrusion is inti-

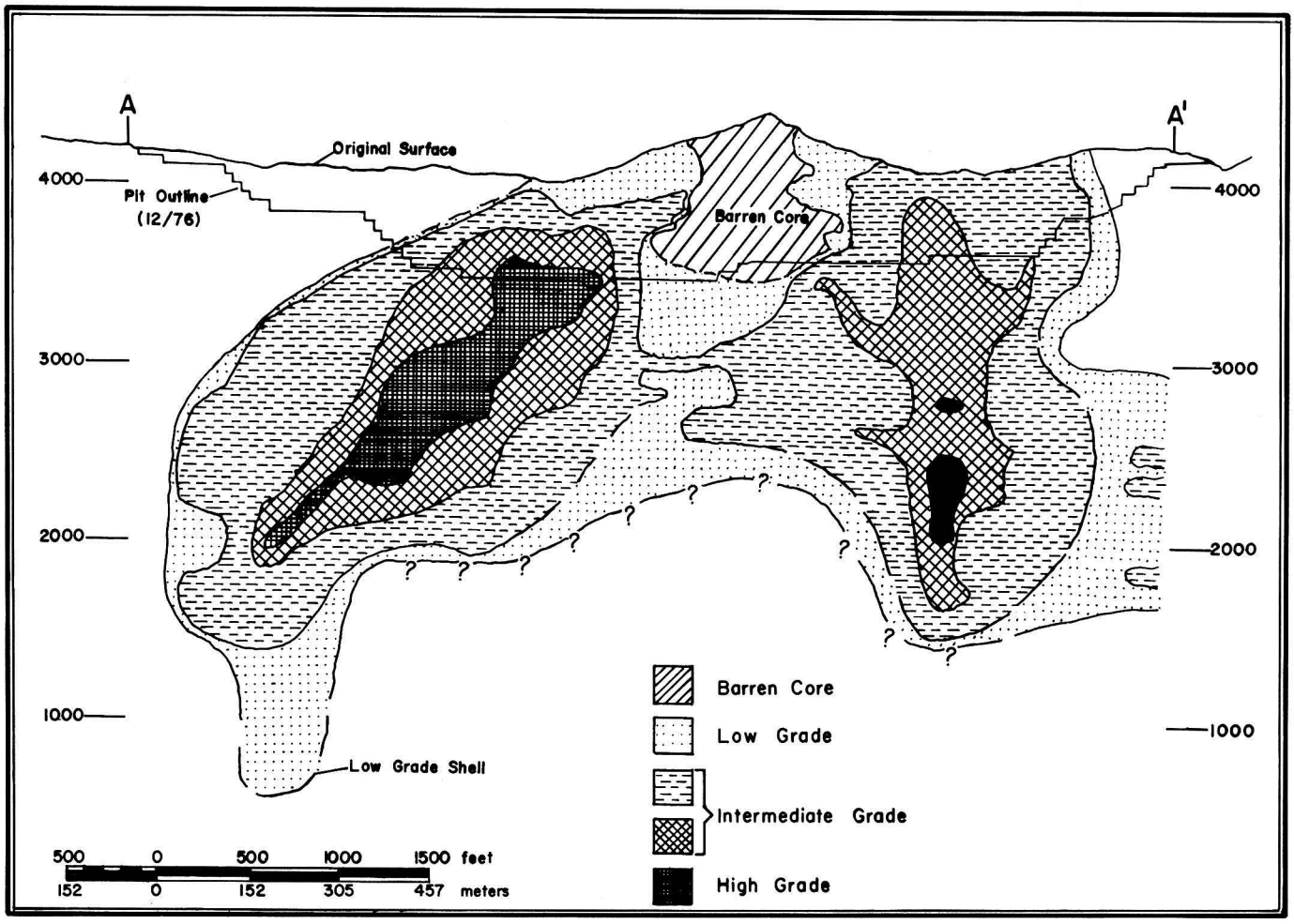

Fig. 3. Section A-A', showing distribution of economic mineralization at Sierrita

mately associated with mineralization and alteration and is considered to be the source for the metal-bearing hydrothermal solutions. Several variable textures in the Ruby Star quartz monzonite porphyry may suggest successive periods of intrusive activity, or they may be contemporaneous and represent different zones in the cooling magma.

The Ruby Star quartz monzonite porphyry occurs as a central stock with several smaller quartz monzonite porphyry bodies marginal to it. These bodies are irregularly shaped and trend northwestward, reflecting a major regional structural trend. Both the lateral and vertical extent of the porphyry are much greater than might be inferred from surface exposures. The stock has generally not penetrated through the older volcanic and intrusive rocks in the southern part of the mine area. The contact on the north, between the quartz monzonite porphyry and its parent, the Ruby Star granodiorite, is commonly gradational.

Mineralization in the Ruby Star quartz monzonite porphyry occurs predominantly as chalcopyrite, pyrite, and molybdenite fracture fillings, but chalcopyrite and pyrite are also present as disseminations and blebs.

Sierrita Intrusive Breccia. Several irregular breccia masses occupy an area in the eastern portion of the Sierrita pit. These are remnants of a much larger, roughly east-west-trending body. In the upper levels of Sierrita, clasts derived from the Ox Frame volcanic rocks, Harris Ranch quartz monzonite, Ruby Star quartz monzonite porphyry, and biotite quartz diorite are common in the breccia body. The lower part of the breccia as exposed on the 3600 level is composed of subangular fragments, typically Ruby Star quartz monzonite porphyry. The clasts become more angular toward the edges of the breccia zone. Fragments are set in a matrix of fine-grained biotite, rock flour, silica, and some magnetite. The shape and distribution of breccia masses and pods

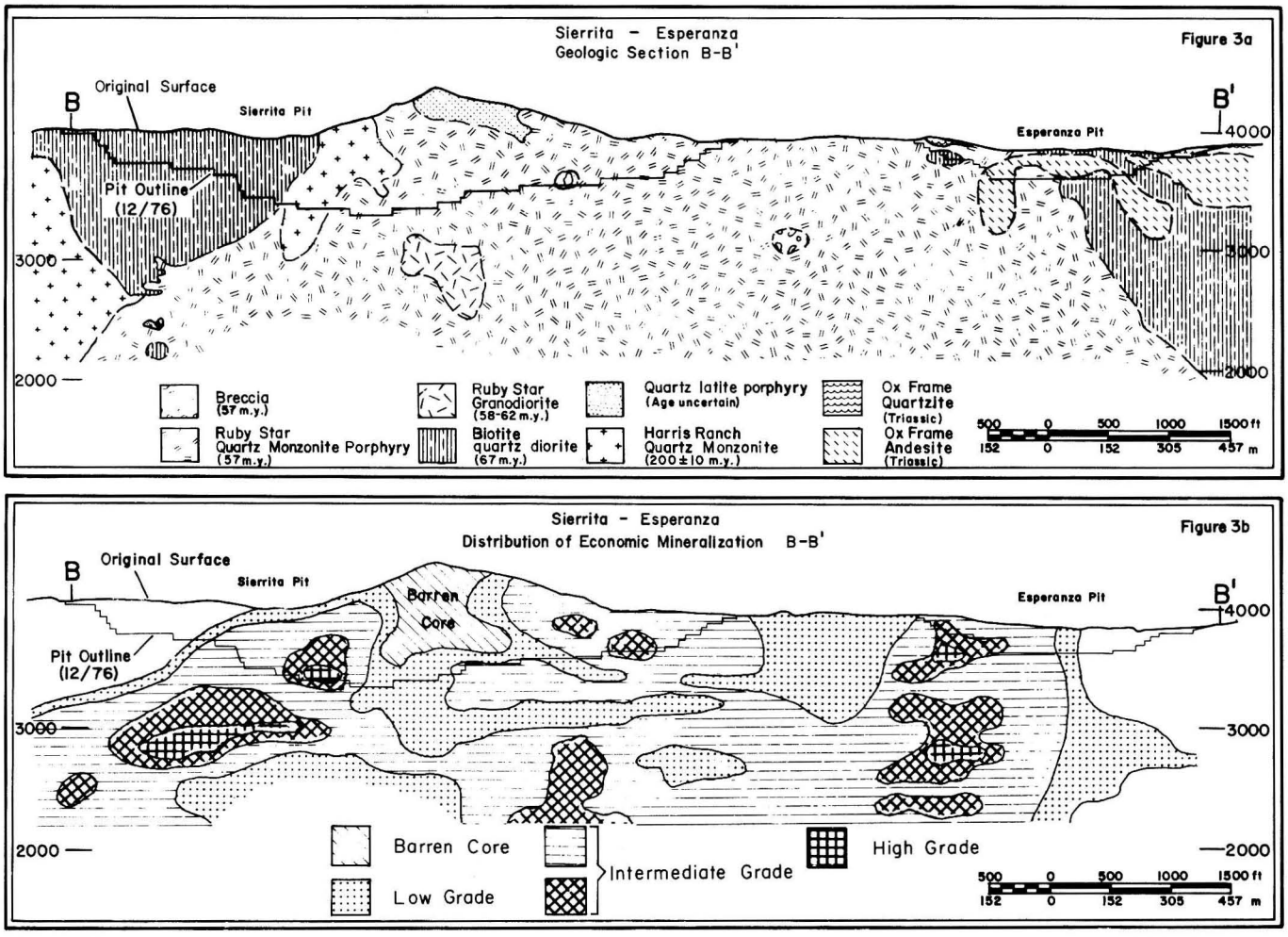

Fig. 4. Section B-B': (a) Geology of the Sierrita-Esperanza deposit; (b) distribution of economic mineralization

(Fig. 2) suggest that the unit is related to Ruby Star quartz monzonite porphyry and was developed by the channeling of magmatic fluids up irregular conduits and fissures. These structural controls were probably associated with stockwork fracturing caused by the emplacement of the quartz monzonite porphyry pluton in the mine area.

The zone of brecciation expands laterally along rock contacts near the 3900 elevation (Fig. 2) and fingers out in Ox Frame andesite, biotite quartz diorite, and other units that crop out on the pre-mine surface. This may explain the relative abundance of mafic fragments in upper breccia occurrences as noted earlier. The configuration of breccia as described above may be as much as 2500 feet long and 600 to 1000 feet wide in the upper body but narrows below the 3750 bench typically into discontinuous bodies of variable size.

The breccia is generally characterized by moderate alteration of fragments, biotite flow features around clast edges, relatively large fragments with little microbrecciation, and a dark, dense matrix composed mainly of fine-grained biotite with rare open channels or vugs.

Copper and molybdenum mineralization in the breccia, good in upper levels of Sierrita, diminishes with depth. Apparently, the increased grade in the upper part of the breccia is related to the abundance of (receptive) fragments of Ox Frame andesite, biotite quartz diorite, and Harris Ranch quartz monzonite.

Mudd Hill Breccia. A distinctive intrusive(?) breccia exists south of Esperanza (Fig. 1), now partially covered by waste dumps. The hydrothermal alteration of the breccia is unusually intense compared to other breccia occurrences in the deposit. Strong quartz-sericite alteration has almost completely de-

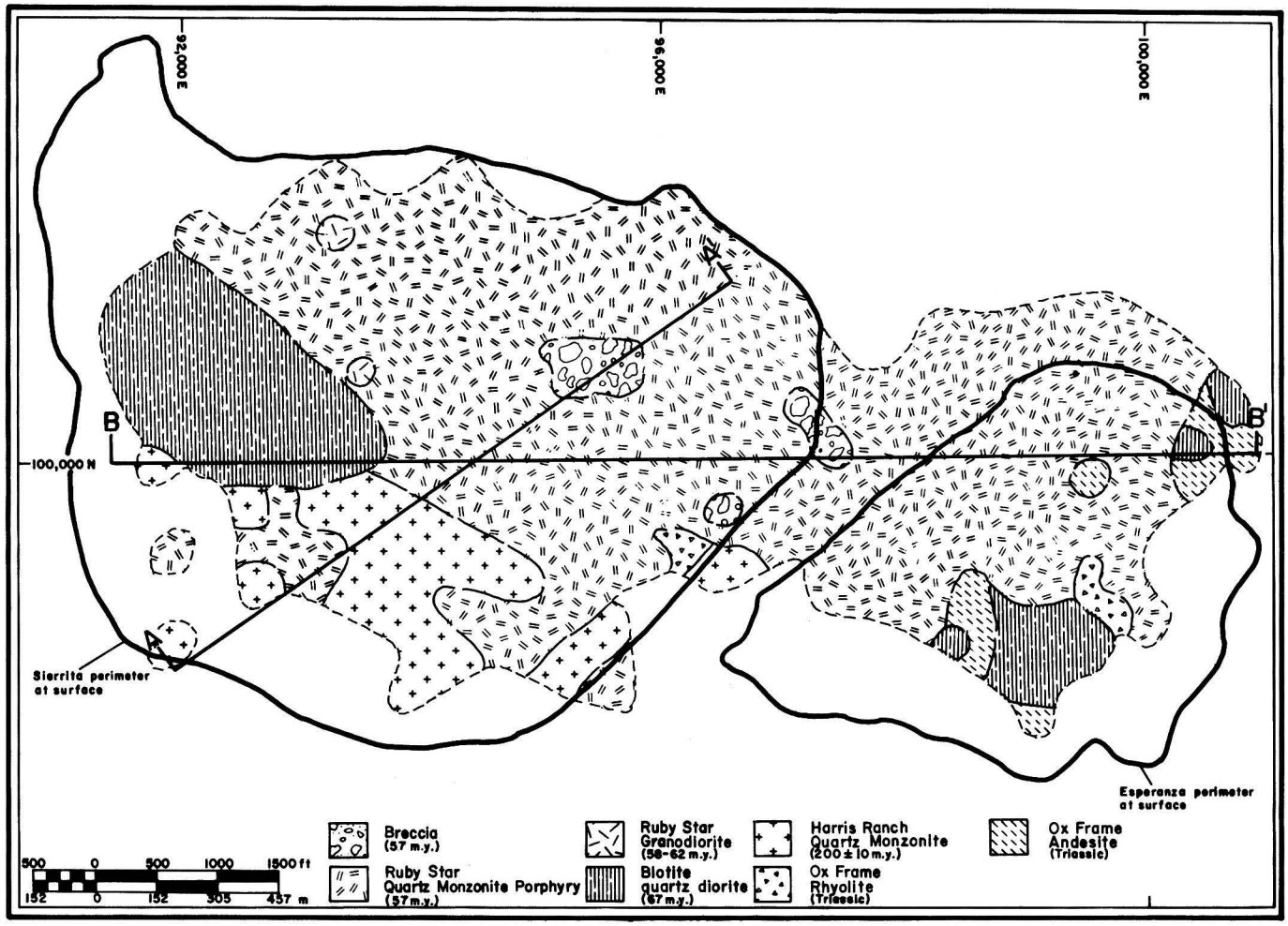

Fig. 5. 3200 bench, showing Sierrita-Esperanza deposit geology

stroyed angular and rounded fragments of andesite and quartz latite porphyry set in a pyrite-silica matrix. This breccia has sparse economic mineralization.

Contact Breccia. Brecciation at Sierrita is also common along the contacts of the Harris Ranch quartz monzonite, biotite quartz diorite, and Ruby Star quartz monzonite porphyry. Reworking of inclusions detached from the country rock during multiple episodes of intrusive activity has resulted in localized breccia masses of intermixed angular fragments, and chilled and hybrid contact zones.

Quartz Latite (Porphyry). At Sierrita, Tertiary porphyritic quartz latite dikes cut all rock types, including the Laramide Ruby Star intrusions, indicating two periods of igneous activity involving similar rock types in the Sierrita-Esperanza system. The dikes are mineralized with pyrite and chalcopyrite fracture coatings.

Structures and Characteristics of Orebodies

Hypogene sulfide mineralization in the Sierrita-Esperanza deposit consists of pyrite, chalcopyrite, and molybdenite with comparatively minor amounts of galena, sphalerite, magnetite, tennantite-tetrahedrite, and rare marcasite, cubanite, and bornite(?). Within the ore zone, the pyrite-chalcopyrite ratio is roughly 1 to 2; total sulfide content is normally 1 to 2 percent or less, seldom exceeding 3 percent by volume. This ratio increases to greater than 20 to 1 in the propylitic zone, with total sulfide content estimated at 1 to 3 percent.

Mineralization at Sierrita-Esperanza is structurally and lithologically controlled. Linear mineralized zones, for example, parallel or girdle fault trends and intrusive contacts (Fig. 4). In addition, hypogene mineralization is associated with specific rock types and is generally fracture controlled within

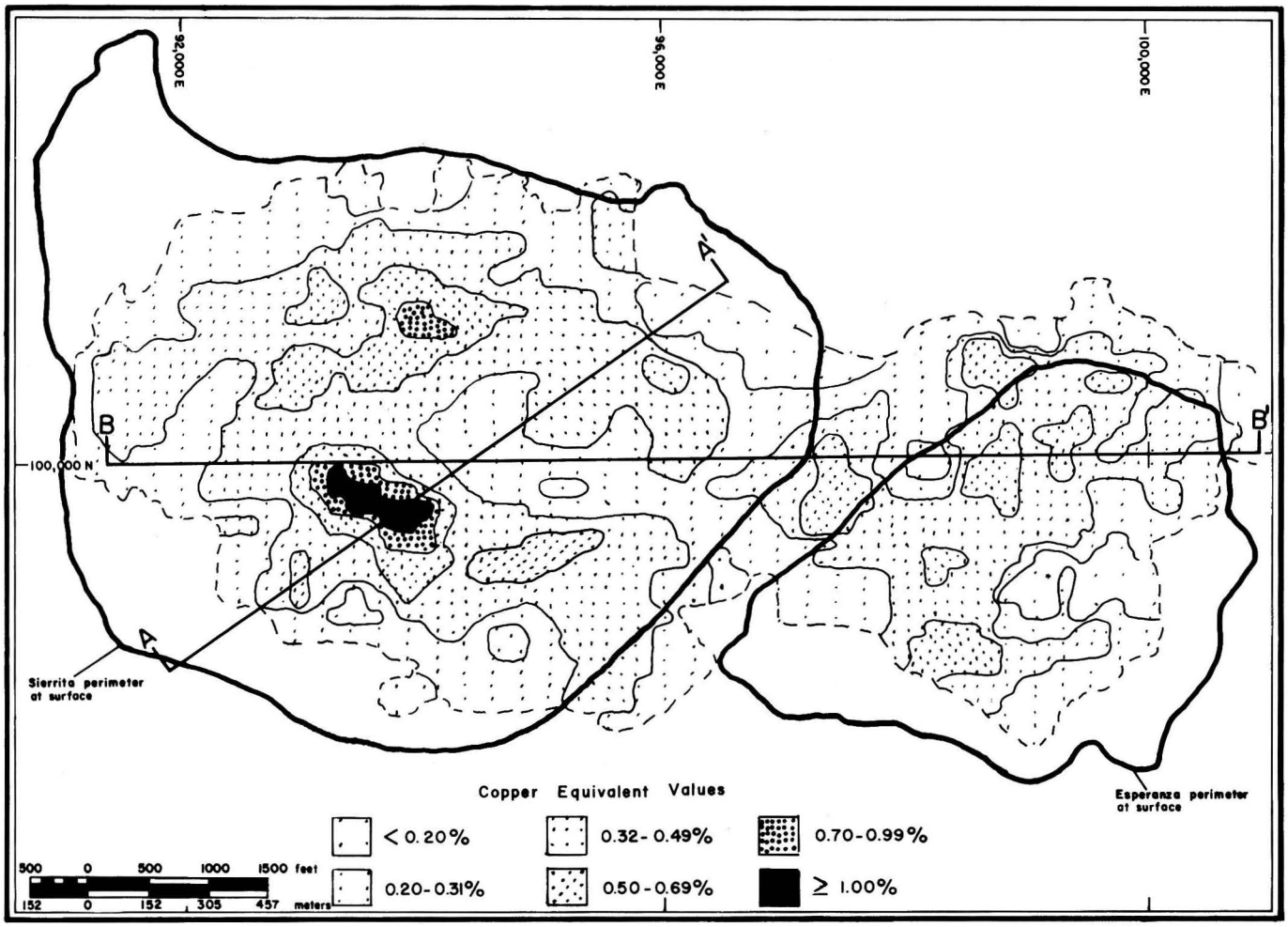

Fig. 6. 3200 bench, showing distribution of mineralization at Sierrita-Esperanza

these units. A dominant system of N. 50°-85° E. and N. 5°-25° W.-trending, steeply dipping, mineralized fractures occurs at Sierrita. The east-northeast fracture set is most strongly mineralized and parallels a major structural trend in the mine area. Also, the east-northeast mineralized set appears to be superimposed on the northwest-trending ore zones, coincident with contacts between the Laramide Ruby Star quartz monzonite porphyry, biotite quartz diorite, and Harris Ranch quartz monzonite. Mineralization and alteration are controlled by this composite structural framework.

Mineralization at Esperanza, occurring mainly in Ruby Star quartz monzonite porphyry, trends N. 40° E., approximately parallel to the contact between the Ruby Star quartz monzonite porphyry and Triassic Ox Frame rhyolite. Economic concentrations also occur in Ox Frame andesite and biotite quartz diorite, which are good hosts (Figs. 5 and 6). Another Esperanza ore zone extends northwestward into Sierrita (Fig. 4b).

The hypogene Sierrita orebody is composed of two major parallel mineralized zones. The east zone, which connects with Esperanza to the southeast (as noted above), occurs in the Ruby Star quartz monzonite porphyry and breccia. The west zone occurs primarily in biotite quartz diorite, Harris Ranch quartz monzonite, and Ruby Star quartz monzonite porphyry. This zone may trend into Esperanza (Fig. 6).

Deep drilling indicates that the west Sierrita zone plunges steeply (60°-80°) westward. A similar configuration exists for the east zone (Fig. 3). These two zones expand laterally with depth and are connected by a well-mineralized, northeast-trending crossover zone in northwest Sierrita to form a concentric zone enveloping a central barren core (Fig. 3). The barren core, as shown on Figures 3 and 6, is roughly 900 feet long and 600 feet wide. This "barren" area has a copper equivalent of less than 0.20 percent. Below the 3500 level, min-

eralization increases to economic grade.

As discussed above, mineralization is primarily associated with fracture fillings and veinlets. Disseminated mineralization is less common. The paragenetic sequence of veinlet formation (oldest to youngest) recognized at Sierrita is as follows:

1. Biotite.
2. Quartz-anhydrite-orthoclase.
3. Quartz-orthoclase-chalcopyrite-molybdenite-pyrite.
4. Quartz-sericite-chalcopyrite-molybdenite-pyrite.
5. Sphalerite-galena with quartz-chalcopyrite-pyrite.
6. Quartz-molybdenite.
7. Quartz-pyrite-sericite.
8. Gypsum and zeolites.

Alteration

Hydrothermal alteration at Sierrita and Esperanza is primarily controlled by the composition and reactivity of host rocks and regional and local structures.

Potassic Metasomatism

Potassic metasomatism is the most significant and widespread alteration in the deposit. The potassic zone encompasses much of the central portion of the Sierrita pit and the northern half of Esperanza, with localized occurrences northeast of Sierrita. The potassic mineral assemblage includes secondary orthoclase and biotite, accessory anhydrite, and in some places, quartz, sericite, and epidote (Smith, 1975).

Secondary potassic feldspar is more widespread than secondary biotite in the deposit and occurs most commonly in the felsic to intermediate rocks at Sierrita. It occurs as:

1. Unmineralized K-feldspar veinlets.
2. K-feldspar-chalcopyrite-pyrite-chlorite veinlets.
3. K-feldspar flooding, which often destroys the original rock texture completely.

Secondary biotite is common in the biotite quartz diorite, the Sierrita breccias, and in the Harris Ranch quartz monzonite at Sierrita and the mafic rocks at Esperanza. It is present mainly as:

1. Fine-grained alteration halos around quartz-sulfide veinlets.
2. Coarse-grained fracture fillings.
3. Zones of flooding which replace or displace other minerals (as in certain brecciated zones).
4. Recrystallization of primary groundmass biotite and hornblende in the biotite quartz diorite.

Anhydrite is a common accessory mineral in the potassic zone and is present in all rock types at Sierrita, particularly the biotite quartz diorite. Epidote, which is not normally recognized as part of the potassic zone, appears to have an intimate relationship with some of the early-formed vein systems at both pits. It appears to have been generated as a companion mineral to secondary orthoclase (Smith, 1975; Titley, 1975). At least some of the epidote observed in this environment may be attributed to retrograde effects and related to temperature fluctuations which accompanied the complex Laramide intrusive activity.

Quartz-Sericite Alteration

Quartz-sericite alteration occurs throughout the deposit and is relatively intense in east Esperanza. At Sierrita, quartz veining with sericite alteration envelopes occurs within and peripheral to the potassic zone and diminishes with depth. The distribution of this assemblage is the result of several periods of hydrothermal fluid circulation as indicated by (1) the offsetting and crosscutting relationships of veins; (2) the varied thicknesses of selvages; and (3) varied vein trends and sulfide content in individual specimens.

An early phase of quartz-sericite alteration accompanies chalcopyrite (and molybdenite) mineralization. A later stage of quartz-sericite-pyrite alteration cuts all fractures except for those containing gypsum and zeolites.

Other Alteration Types

Argillic alteration is mainly restricted to faults and fractures and no major pattern has been delineated. Much of the clay alteration in the upper levels of the mines may be attributed to supergene effects.

Propylitic alteration is prominent at Sierrita and Esperanza and forms a gradational halo around the potassic and phyllic zones. Ore limits roughly coincide with the boundary between the propylitic and higher grade alteration assemblages.

Chlorite and epidote are two of the most important minerals in the propylitic zone, mainly from alteration of the mafic minerals and plagioclase. In Harris Ranch quartz monzonite, the biotite becomes progressively more chloritized toward west Sierrita. In biotite quartz diorite, epidote is pervasive. Minor albite veining is

observed in the propylitic zone at Sierrita. Locally intense groundmass albitization is also recognized. Recent work at Esperanza indicates that at least some albite alteration accompanied potassic metasomatism and metallization (Smith, 1975). However, insufficient petrographic work has been completed to determine the extent of albitization at Sierrita.

Stilbite and other zeolites are commonly found with gypsum in veins and fissures within Harris Ranch quartz monzonite, biotite quartz diorite, and Ruby Star quartz monzonite porphyry.

Gypsum as selenite, alabaster, and satin spar is widespread throughout both Sierrita and Esperanza and occurs as pseudomorphs after or replacements of anhydrite or as post-mineral fracture fillings.

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GEOLOGY OF THE LA VERDE COPPER DEPOSITS, MICHOACAN, MEXICO

by

D. V. Coochey and Philip Eckman [1]

Abstract

La Verde is in the state of Michoacán, 200 miles west of Mexico City. The deposits are on the Sierra del Marqués, an east-west-trending range nearly 4 miles long largely made up of quartz diorite intruded by acidic dikes and stocks. On what is called the East Hill there is one deposit in a quartz feldspar porphyry stock and three others in diorite breccia and crackle breccia adjoining it. Mineralization is chalcopyrite and bornite in varying proportions among and within the four orebodies, with only a very minor pyrite content. Hydrothermal alteration is present but generally weak. On the West Hill, centered a mile west of the East Hill orebodies, there is a single zone about 2,000 feet long and up to 800 feet wide, trending north-south. Mineralization is largely confined to steeply dipping, east-west-trending veins carrying pyrite, pyrrhotite, and chalcopyrite, and there are dozens of them. There is a selvage of intense silica-epidote-sericite alteration bordering these veins, but the diorite between them is only slightly altered and is nearly barren. Mineralization in both the East and West Hills extends to the greatest depths drilled up to 1,200 feet vertically below surface with no significant change in grade or character. Oxidation extends to varying depths up to about 200 feet, but there is no leached zone and no chalcocite blanket. The grade of the ore in the oxide and sulfide zones is about the same.

Introduction

There are many copper deposits known as La Verde in Mexico, but this one is located in the state of Michoacán, 320 km west of Mexico City and 220 km by highway inland from the Pacific Coast port of Lázaro Cárdenas (Fig. 1). La Verde was worked in a small way many decades ago, and some 50,000 tons of ore were mined underground from high-grade sections, hand sorted, and material grading 10 percent copper or better was shipped. The information on which this paper is largely based was developed in the course of exploration carried out in the years 1967-72, which included extensive tunneling, core and percussion drilling, bulk sampling, and geologic mapping of the surface and underground workings carried out by the senior author. Substantial ore reserves have been delineated at two locations. The concessions are held by Cia. Cuprífera La Verde, S.A., and a production decision awaits favorable conditions in the copper industry and an examination of the overall viability of the project.

Topographically, the location is in the valley of the Río Balsas, just south of the Central Volcanic Belt of Mexico. Several volcanic cones can be seen from the site, the closest about 3 km away. Locally, the deposits are on the Sierra del Marqués, an east-west-trending, arc-shaped range of hills 6 km long that rises to a peak elevation at Cerro Camacho of 730 m, 200 m above the plan elevation on the north side and 300 m above it on the south side. The property is unusual in that a paved highway, a branch line of the Na-

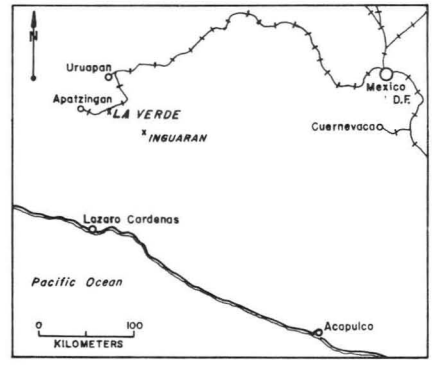

Fig. 1. Location map

[1] Beaver Exploration Company, Tucson, Arizona 85718

[2] Phelps Dodge Corporation, Ipanema, Rio de Janeiro, Brazil

tional Railways of Mexico, major power lines, major power lines, and a river all pass through it.

Regional Geology

The host rocks are phases of the Huacana granodiorite-quartz diorite pluton, which is 70 km long and trends northwest. It is the northernmost member of a cluster of plutons in southern Michoacán, which in turn is one of a series of clusters extending up the west slope of the Sierra Madre Occidental into Sonora, many of which have associated copper deposits. There are four known porphyry copper deposits within the Huacana pluton where it is intruded by younger porphyries with associated igneous breccias, namely, La Verde, Inguarán, San Isidro, and Manga de Quimo.

This region of Mexico is characterized by basin-and-range topography trending east-southeast; the basins are filled with thick sequences of bedded conglomerate, thin sandstones and mudstones, and recent volcanic rocks. At La Verde, the absence of pebbles of intrusive rocks in the conglomerates and their presence in talus fans and old river fill cutting through the conglomerate point to the very recent unroofing of the pluton. Though age has not been radiometrically determined, this series of intrusive rocks is classed as Cretaceous on government geological maps; the andesitic lavas that cap many of the ranges are Tertiary.

La Verde Geology

The Sierra del Marqués in which the deposits occur is totally composed of intrusive rocks, mainly quartz diorite, for convenience called the La Verde intrusive complex. It is divided into two fundamentally different units known as the East and West Hills, the point of separation being at the center of the arc-shaped range (Fig. 2).

The East Hill unit is characterized by abundant aplite and quartz feldspar porphyry stocks intruding medium-grained quartz diorite and the development of large breccia zones which carry the bulk of the mineralization. Simple crosscutting relations suggest two phases of acid intrusion and related breccia development.

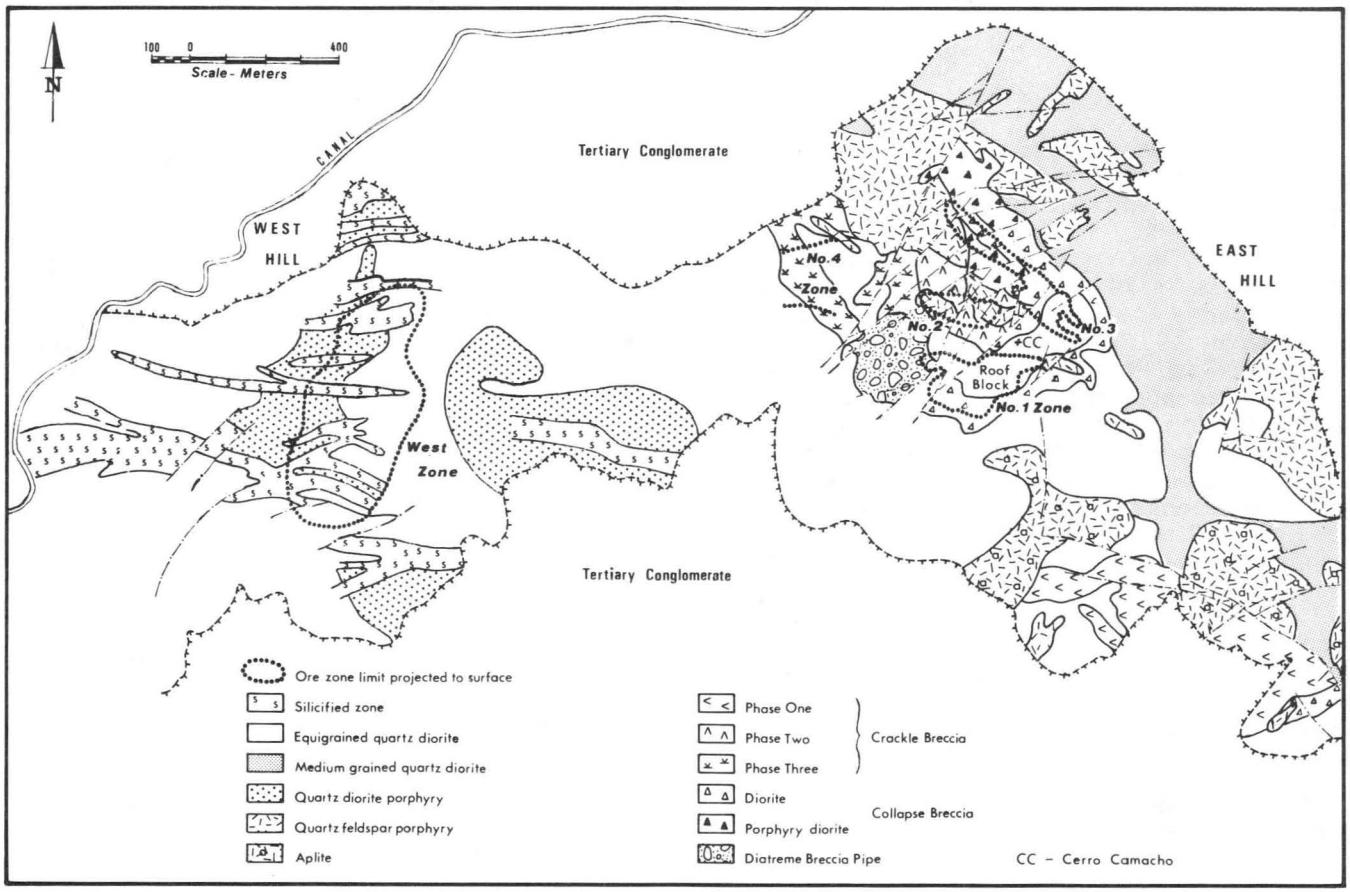

Fig. 2. Geological plan map, Sierra del Marqués

The West Hill unit is characterized by irregular bodies of quartz diorite porphyry in the medium-grained quartz diorite, and except for a few thin dikes in the diorite, acid intrusive rocks are absent. Mineralization is confined to replacement and fracture filling in sheeted vein systems of which the most important—the West Hill orebody—lies across the contact of one of the quartz diorite porphyry bodies.

The quartz diorites are massive grayish-green rocks composed mainly of oligoclase-andesine, hornblende, and quartz. In the medium-grained quartz diorite the feldspar is weakly sericitized and the hornblende partly chloritized throughout the Sierra del Marqués. Grain size is 2-5 mm, and quartz is interstitial. The quartz diorite porphyries are fresher in appearance, with phenocrysts of lilac-gray andesine and hornblende in a matrix of fine-grained feldspar (occasional potash feldspar), and quartz. Contacts of the quartz diorite porphyry and medium-grained quartz diorite are both gradational and sharp, never chilled, with little or no contact alteration.

The acid intrusive rocks are white, gray, and yellowish, both massive and strongly fractured. On the south slope of the East Hill they are predominantly aplites, with typical subgraphic and myrmekitic textures, and these appear to grade into quartz feldspar porphyries in some localities. The porphyries form stocks and irregular dikes in the center and north slope of the East Hill. They consist of 60 percent albite-oligoclase and 25 percent "bird's eye" quartz phenocrysts, with minor chlorite laths. Chilling and flow structures are common, and occasionally biotite develops in diorite and porphyry at the contacts of the stocks, while the centers tend toward equigrained textures.

The East Hill Complex

Two phases of acid intrusive rocks and three of breccias have been identified.

Phase One breccia is only developed in the southeast part of the Sierra del Marqués as an east-southeast-trending band of diorite crackle breccia 250 m wide with many large blocks of diorite. This breccia is thought to be early because it is intruded by aplite stocks and dikes of the first acid intrusive phase. Mineralization is weak or absent.

Phase Two breccias occur in an area 600 m in diameter centered on Cerro Camacho, and host two of the East Hill ore zones (Fig. 3). True breccias crop out as a band 30 to 150 m wide extending around the southern and northeastern slopes of the cerro. These breccias form a boat-shaped or elongate, inverted cone-shaped mass 500 m wide at surface, tapering to 200-250 m wide at a depth of 200 m. The sides of the cone dip 45-50 degrees toward the center except in the extreme northwest area where the breccia band is nearly vertical. The center of the cone is occupied by equigrained diorite crackle breccia and a "roof block" of unbrecciated diorite. Its lower contact is sharp, and the footwall is formed mainly of medium-grained quartz diorite. The upper contact is gradational, and massive quartz diorite grades downward into weakly then strongly crackle brecciated quartz diorite and finally coarse breccias. These have subangular to angular fragments of all quartz diorite phases, quartz feldspar porphyry, and minor aplite and quartz, 0.5 to 20 cm in diameter, in a cataclastic matrix of rock fragments and broken crystals of quartz, feldspar, and chlorite, which forms 10 to 40 percent of the volume of the breccia. Large blocks of unaltered diorite and porphyry and rare aplite up to several meters across occur in the breccia. Bands of distinctive lithologies with fragments of mainly porphyry, of diorite, or of mixed porphyry and diorite can be traced through it. Zones in which the fragments are mainly coarse (over 5 cm in diameter) or fine (1-5 cm in diameter) can also be identified, and dip toward the center of the cone, roughly parallel to its contacts. These facts, and also the texture of the breccia, its contact relationships, and conical form advocate formation by collapse. This would require a low-pressure volume to be developed at the apex of the cone into which the brecciating blocks subside. This space is occupied by a quartz feldspar porphyry intrusion (Fig. 4).

This porphyry of the second phase is best exposed on the adit level of the East Hill. Here it is elliptical in plan, 300 m long by up to 150 m wide, trending east-southeast. It is elliptical in cross section also and has the overall shape of a dike that has "ballooned" in the collapse breccia zone. No breccia xenoliths have been observed in the porphyry, but its southern half contains many inclusions of dioritic feldspar partly replaced by biotite and chlorite. It is speculated that intrusion occurred in two phases. A proto-intrusion was first emplaced passively and assimilated part of its diorite host. Magma pressure then dropped, resulting in the collapse of a cone of diorite around it, then subsiding diorite blocks squeezing new porphyry magma up into the breccia zone. The relaxation of magma pressure from the thin feeder dike into the larger tube would release large volumes of volatiles to lubricate breccia formation and "pump up the balloon."

Phase Three breccias form a band 700 by

Fig. 3. Plan of adit level, East Hill

300 m southwest of the Phase Two breccias, completing the ring of breccias around the Cerro Camacho. They consist of three units which crosscut or rebrecciate previously formed breccias and associated quartz feldspar porphyry. From southeast to northwest these are:

1. A breccia pipe about 200 m in diameter, with well-rounded fragments of all La Verde rock types in a matrix of pulverized rock and chlorite with abundant albite-oligoclase feldspar laths matching those in the quartz feldspar porphyry. The pipe is considered to be of diatreme origin formed by the injection of acid porphyry highly charged with volatiles. Two large blocks of andesite lava have been found in the pipe, indicating that it extended up into the covering volcanics which have since been stripped off by erosion.

2. A crackle breccia rim flanks the diatreme to the north; its matrix is essentially continuous with it. This crackle breccia clearly crosscuts the collapse breccia of Phase Two, its quartz feldspar porphyry intrusion, and its contained mineralization.

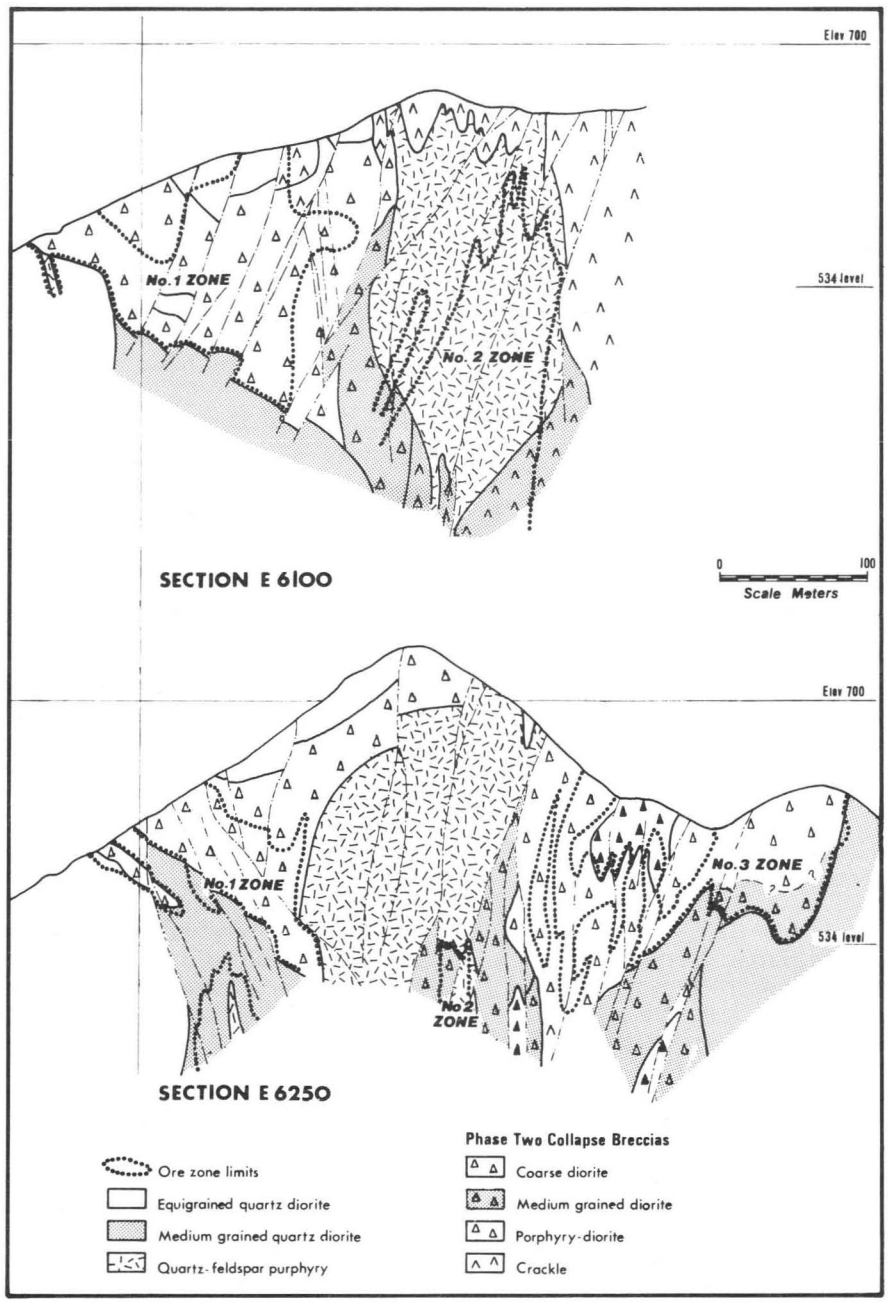

Fig. 4. Cross sections of East Hill ore zones, looking west

3. No. 4 orebody crackle breccia is northwest of the diatreme and appears to be of hydrothermal origin in that its matrix is formed wholly of sulfides and vein minerals.

Alteration and Mineralization of the East Hill Unit.

Phase One breccia shows intergrown pyrite-pyrrhotite with very minor chalcopyrite and arsenopyrite in quartz-calcite stringers and small vugs in the matrix of the breccia. These are the only breccias on the East Hill with significant pyrite, and they develop a thin gossan at surface. Acid intrusive rocks of this phase, mainly aplite, are almost barren.

Phase Two collapse breccia alteration consists of a strong pinkening of the feldspars in the fragments and matrix, extensive epidote and calcite replacement, and sericitization. Propylitization is often so strong as to obliterate breccia textures. There is no doubt that the matrix was the main channelway for solu-

tions, as fragments larger than 20 cm in diameter almost always show a rind of pink alteration around fresh gray interiors.

Following propylitization, the breccias on the south and north sides of the Phase Two quartz feldspar porphyry intrusion were mineralized with bornite and chalcopyrite, minor tennantite and arsenopyrite, and traces of pyrite and molybdenite to form, respectively, the No. 1 and No. 3 orebodies. Sulfides occur as discontinuous stringers, fracture coatings, blebs, and fine disseminations throughout the matrix and fragments of the breccia. They frequently concentrate at fragment-matrix boundaries. On average, the bornite-chalcopyrite ratio is 2:1, but the distribution is uneven. The rim of the breccia cone in both No. 1 and No. 3 orebodies is usually chalcopyritic, with successive zones of mixed bornite-chalcopyrite and bornite toward the center of the cone. This zoning pattern is cut across by northeast-trending faults containing vuggy stringers of chalcopyrite and calcite and strongly sericitzed borders. The faults are only mineralized within the breccia, becoming barren when they pass out of it on strike. Mineralization is strongest in the outer rim of the breccia cone, with up to 5 percent sulfides, and cuts across the boundaries of the various Phase Two breccias, but sharply weakens to much below ore grade in the adjoining massive diorite.

Phase Two quartz feldspar porphyry contains near its northern contact a mineralized, sheeted vein structure known as No. 2 orebody. It trends parallel to the east-southeast-trending contact of the porphyry with collapse breccia, averaging 60 m wide. The zone consists of swarms of seams of copper sulfides, parallel and spaced one to a few centimeters apart, with selvages of silica-chlorite alteration with finely disseminated sulfides. The southern edge of the zone is mainly chalcopyrite, the center bornite-chalcopyrite, and the northern half bornite. Mineralization fades out in porphyry to the east and in breccia to the west and at depth.

Phase Three breccias all show development of greenish sericite, chlorite, and calcite in fragments, but to only a slight to moderate degree. Only a few minor lenses of ore occur in the diatreme and in its crackle breccia rim. Although the No. 4 crackle breccia extends through to surface, ore-grade mineralization begins only at 100 to 200 m below surface, where all interfragment space is occupied by bornite-chalcopyrite in a calcite-quartz-tourmaline gangue. No true matrix has been observed, and the breccia is considered to be of hydrothermal origin.

Following emplacement of the East Hill orebodies, slight silica-sericite alteration occurred along northeast and east-southeast fractures. This alteration is essentially barren of sulfides.

A series of northeast- to east-northeast-trending normal faults cuts through the East Hill orebodies. The major faults dip steeply southeast, and the conjugate set dips steeply northwest. The faults are in effect components of a small graben cutting northeast across the East Hill.

The West Hill Complex

On the West Hill three quartz diorite porphyry stocks intrude the equigrained quartz diorite. The westernmost stock, which is host to part of the ore zone, trends north-northeast. West of it the equigrained quartz diorite was affected by pervasive deuteric alteration over an area of several square kilometers in which feldspars and hornblende were replaced by microscopic aggregates of hematite-quartz-chlorite to form a reddish rock called "red diorite." Intrusive events terminated with the injection of a few dikes of aplite and quartz feldspar porphyry trending east-southeast.

The West Hill orebody is a north-northeast-trending zone 700 m long and 250 m wide straddling the contact of the westernmost quartz diorite porphyry stock with equigrained quartz diorite (Fig. 5). The zone includes three vein systems trending east-northeast, east-west, and east-southeast. Veins in the stock strike principally east-northeast; in the adjacent equigrained diorite east-southeast, and the east-west direction is common to both rocks. Individual vein zones thus describe a broad arc convex to the north, similar to that of the Sierra del Marqués as a whole. All veins are vertical or dip steeply south.

The veins contain pyrite, pyrrhotite, chalcopyrite, and minor arsenopyrite in a gangue of quartz, calcite, and tourmaline, with intense development of epidote, sericite, and quartz in the adjoining host diorite, so that its texture is totally destroyed. Individual sulfide veins are up to several meters wide, and vein zones are up to 100 m wide. Sulfides are almost entirely confined to the veins, and where they are widely spaced the host diorite away from the veins is little altered and almost barren. The vein zones are continuous and overall of remarkably uniform grade to the greatest depths drilled, although individual veins show great variations in width and grade over short distances on strike and dip. Overall, the pyrite content is about

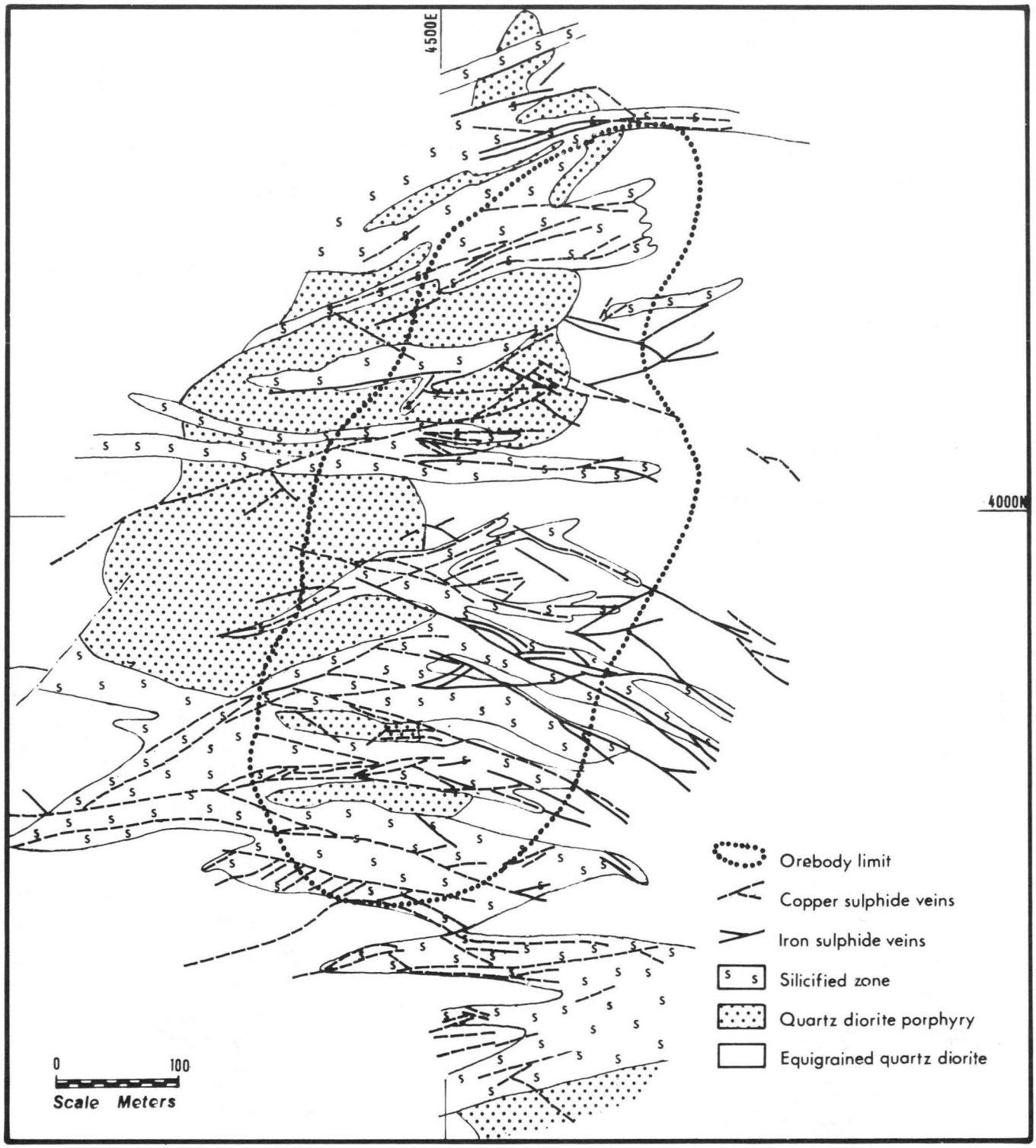

Fig. 5. Plan of West Hill orebody

3 percent and chalcopyrite 1.5% by weight. On strike to the east and west the sulfide veins simply fade out in the diorite. Wide zones of silica-epidote-sericite alteration are found in the diorite both east and west of the orebody but show only weak sulfide mineralization, except for minor pyrite and pyrrhotite in the red diorite.

No large acid intrusion crops out in the vicinity of the West Hill orebody, although it is speculated that one may occur at depth beneath it.

Exploration

Geological Mapping

Surface geology was mapped at a scale of 1:1000 for 4 km of strike length covering the central portion of the Sierra del Marqués. The topographic base at that scale was prepared from aerial photographs with a 2-m contour interval. All underground workings were mapped at 1:200.

Geochemical Survey

Soil samples were taken on north-south-bearing lines generally 100 m apart, at intervals of 25 m, and were assayed for copper only. All of the orebodies except No. 2, which does not crop out, are contained within the +500 ppm copper anomaly, and results can be contoured up to 4,000 ppm copper over the outcropping No. 1, No. 3, and the West Hill orebodies (Fig. 6).

Induced-polarization Survey

Extensive surveys in the time domain were carried out on the lines 100 m apart and showed almost the entire Sierra del Marques to be anomalous, with chargeabilities up to 30 milliseconds. Individual highs within the major anomaly are offset 100 to 200 m from the actual orebodies (Fig. 7).

Tunneling

A total of 3,386 m of tunnels were driven on both East and West Hills to provide geological data, bulk sampling material, and sites for underground drilling.

Drilling

Inclined holes were drilled on section lines 50 m apart, mainly bearing north-south. Several holes were drilled on each section, laid out generally so as to provide intersections at a spacing of not more than 50 m. A total of 48,559 m in 233 holes were core drilled, and 12,275 m in 279 holes by percussion drilling. Core recovery averaged 85 percent on the East Hill and 94 percent on the West Hill.

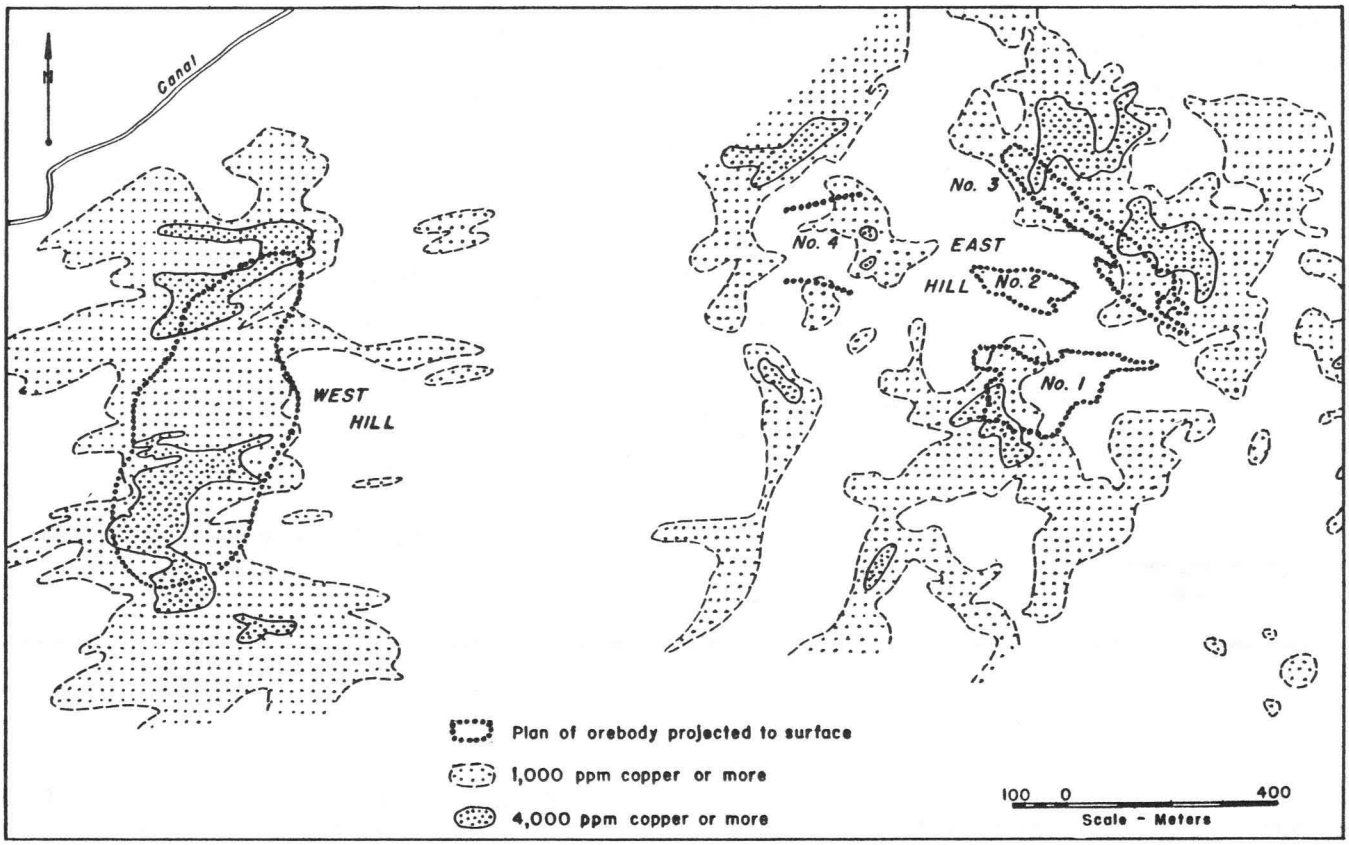

Fig. 6. Orebodies and soil geochemical anomalies, Sierra del Marqués

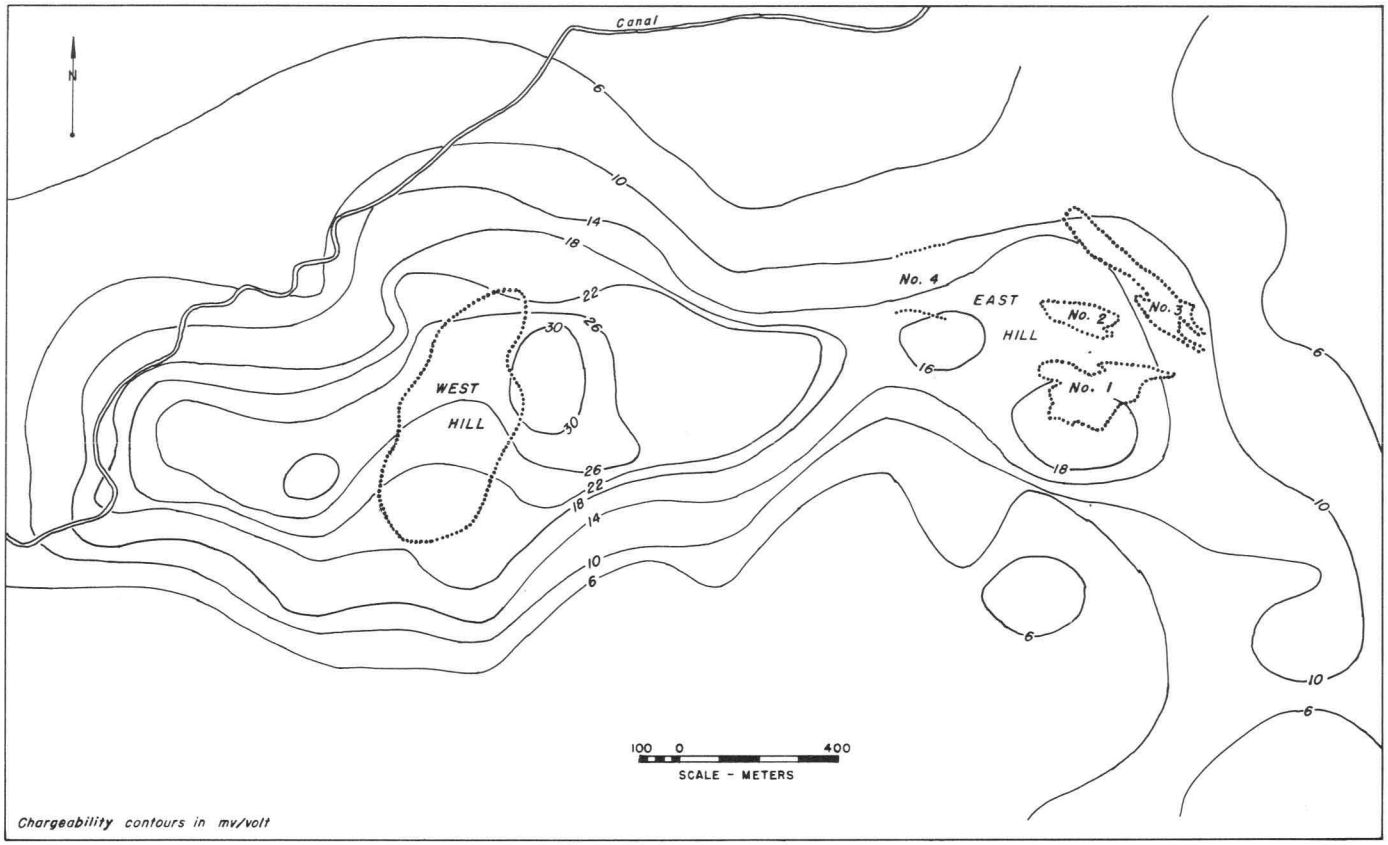

Fig. 7. Orebodies and induced-polarization anomalies

Sampling

Percussion drill holes were sampled at intervals of 2 m, core holes at varying intervals of up to 3 m, and face and car samples were taken from all tunnels driven. As a guide to the credibility of the various sampling methods, a total of 245 m of tunnel in various locations on both hills were driven on the line of a flat diamond drill hole and a flat percussion hole parallel to and a foot or so from the diamond drill hole, and the entire volume of rock, amounting to about 3,000 metric tons was put through a crushing and sampling plant, round by round, to provide a bulk sample. A comparison of the overall average results shows:

	East Hill	West Hill	Total
Meters driven	136	109	245
Average bulk sample, % Cu	0.99	0.54	0.79
Average car sample, % Cu	0.78	0.40	0.61
Average face sample, % Cu	0.93	0.46	0.72
Average core sample, % Cu	0.89	0.48	0.71

Core recovery averaged 73.7 percent for the East Hill drilling for the tunnel length sampled, 88.2 percent on the West Hill, and 80.1 percent overall. Only 5 out of 11 percussion holes were completed due to failure to penetrate faults, and the results are not comparable. They tended to produce erratically higher results than the bulk sample.

Acknowledgments

The authors are grateful to officials of Cia. Cuprífera La Verde, S.A. for permission to publish this paper, to Ing. Pedro Araujo Moreno for preparation of the illustrations, and to Alastair Walker for critical reading of it. It is a pleasure to record the excellent cooperation of Mexican local, state, and federal government officials during the exploration period, and the outstanding services of Mexican technical personnel and employees that made the entire program possible.

PRODUCTION COSTS, PORPHYRY COPPER MINES, WESTERN UNITED STATES

by

Harry J. Winters, Jr. [1]

Abstract

The cost of copper produced from sulfide concentrates from most United States porphyry copper mines exceeds $0.60 per pound. With rare exception the cost of production from new mines will exceed $0.70 per pound. Only the margin on copper precipitates, molybdenum, and precious metals has kept several mines from slipping into a loss position in the present copper market. An understanding of the effects of geologic factors on production costs has always been very important to achievement of competitive costs, but never more than now. Such understanding is also more essential than ever to evaluation of new projects, expansions as well as new mines, to ensure collection and meaningful compilation of geologic information needed for planning and to make possible an accurate estimate of a project's competitive position.

One of the keys to competitive costs is efficient materials handling from mine through refinery. The system of transportation of ore and waste to beneficiation plants and dumps cannot be well planned without a thorough understanding of the number and distribution of ore types and grade distribution. Inadequate knowledge of ore type and grade distribution, bench by bench, can lead to transportation system bottlenecks which result in very high mining costs per ton of material mined. It can also lead to improper equipment selection with consequent inordinate amounts of walking of shovels and drills and high maintenance costs.

More geologists are needed who can bridge the gap between exploration and planning. The ability to do so will continue to come chiefly from personal initiative, but mining and geology departments of educational institutions should be more active in this discipline.

Introduction

The cost of refined copper produced from western United States porphyry copper ores in almost every case exceeds $0.60 per pound, with the average close to $0.65 per pound. Some mines' costs exceed $0.70 per pound. These costs give full effect to byproduct credits and copper produced from leaching of waste dumps. They include depreciation but do not include any contribution needed, in excess of depreciation, to permit future capital replacement to maintain present levels of copper production or to comply with increasingly burdensome government regulations. They do not reflect the full burden of interest on long-term debt. (The reader is cautioned that the information in this paper reflects 1976 prices and costs. There are substantial differences in 1978 which in the main have caused United States porphyry copper economics to deteriorate.)

The United States has recently gone through the worst inflation in her history, at least since the Civil War. Regrettably it is clear that unacceptable rates of inflation are still not behind us. Since 1972 the hourly costs of operating, maintaining, and repairing mining equipment have more than doubled. The cost of diesel fuel has more than tripled. Costs have doubled and tripled for a kilowatt-hour of electric power. Grinding balls have doubled in cost. Cans used in the production of copper precipitates have doubled or more than doubled.

Important foreign producers continue to be able to produce refined copper at costs significantly lower than western United States costs. The average cost of production from the Philippines may be as much as $0.10 per pound less than the cost of domestic copper. Moreover much foreign production is under the control of governments some of whom are willing to produce from mines operating at a loss in order to maintain employment goals, modulate social unrest and earn foreign exchange in the short run even though such policies may be destructive of the social order in the long run.

[1] Pincock, Allen & Holt, Inc., Tucson, Arizona 85712

At 1976 copper prices, copper deposits with average grades in the 0.45 to 0.55 percent total copper range are in varying degrees of trouble depending on stripping ratio, metallurgical characteristics, and interest rates. It is obvious that we must do everything possible to hold down production costs if copper deposits in the above grade range are to become profitable, producing mines. Cost control begins with proper mine and metallurgical planning. Proper mine and metallurgical planning in large measure means efficient materials handling from mine through smelter.

Mining Costs

Direct open-pit mining costs per ton of material mined lie in the range of $0.30 to $0.55, with most mines in the $0.40 to $0.50 range. There are two pits that have had costs in excess of $0.70 per ton. These costs do not include depreciation and as used in this paper do not include any payroll burden, taxes or insurance on mining equipment, or any allocation of general and administrative expense.

The cost per pound of marketable copper produced will typically lie in the range $0.140 to $0.175 for an ore that yields 10 pounds of copper through refining and is mined with a 2.5-1 ratio (by weight) of waste to ore. A chalcocite ore with a total copper assay of 0.67 percent or a chalcopyrite ore with a total copper assay of 0.59 percent might yield such a recovery. Stripping ratios near 2.5 to 1 are not uncommon.

The principal geologic factors affecting open-pit mining costs are the level-by-level distribution of ore types, ore grades and waste, and structures affecting slope stability. Without good level maps showing these features it is not possible to really plan well the system of transportation of ore from point of loading to the crusher. Waste-to-ore ratios at a given future time cannot be accurately predicted. Mining faces cannot be planned with the most advantageous orientation. Adequate planning for ore-type blending cannot be done.

A good grade and ore-type distribution model permits reasonably accurate estimation of preproduction stripping requirements, yearly waste-to-ore ratios, and availability of ore of different grades and metallurgical types. Good level maps and estimates of the above factors make possible a good haulage plan, which is the key to low mining costs. They permit selection of the equipment best suited to the orebody. Inaccurate stripping estimates can lead to inability to meet debt service requirements with the need for very costly refinancing of obligations. Improper equipment selection can lead to excessive tramming of shovels and drills with increases in hourly operating and maintenance costs of 20 to 40 percent. As shovels increase in size, the importance of an individual unit in achieving production goals become more and more pronounced. A faulty mining plan, due to a lack of good level maps, may lead to many nonproductive hours of shovel walking and downtime and to idle expensive concentrator capacity.

With good geologic level maps and some simple testing it is also possible to predict the extent of rock types with significantly different drillability. Different rock types found in pits in the Twin Buttes district may result in penetration rates with the same drill that differ by a factor of two.

Good grade distribution maps are invaluable in judging the relative merits of shovels and loaders or a combination of the two for a particular orebody.

Milling Costs

Direct milling costs lie in range of $1.20 to over $2.00 per ton of ore milled. Most frequently the costs are in the range of $1.35 to $1.60. The cost per pound of marketable copper for an ore yielding 10 pounds per ton will be $0.135 to $0.160. Inaccurate level maps and consequent poor planning and underachievement of tonnage goals can push the cost over $ 0.20 per pound.

Since mineralogy affects total recoverable pounds, it can have a drastic effect on all costs from mining through smelting. To clarify the effect on milling costs, three situations might be considered:

1. Do we have a clean chalcopyrite ore? Is the sulfide ore liable to be diluted with oxidized material in fault zones or in caving, for example, toward the end of draw of a block?

2. In the case of a chalcocite ore does the chalcocite occur almost entirely as thin coatings on pyrite? Does it extend down into cleavage planes to the extent that substantial copper is still locked up in pyrite at any reasonable grind?

3. If the ore is a mixed oxide-sulfide ore is the oxide mainly chrysocolla, malachite, or a film on chalcocite?

Assuming a direct milling cost of $1.50 per ton of ore milled and a total copper assay of 0.60 percent, the above ores could yield a wide range of costs per pound of copper produced.

The clean chalcopyrite ore might give a recovery through refining of 86 percent with a cost per pound of copper of $0.145. If a significant amount of oxidized material were present, recovery might drop to 84 percent with a cost of $0.149 per pound. A chalcocite ore with the chalcocite as exterior coatings on other sulfide grains might yield a 75 percent recovery with a cost of $0.167 per pound. With a substantial amount of the chalcocite on unexposed cleavage planes at a fine grind, final recovery could drop to 68 percent with a milling cost of $0.184 per pound. Mixed oxide-sulfide ores might give 75 percent recovery after treatment, costing, for example, $3.65 per ton to recover both oxide and sulfide copper. The cost per pound would be $0.405.

General and Administrative Costs

These costs include such items as the unit general manager, accounting, purchasing, safety and welfare, pension plan, insurance, general maintenance, and as used in this paper, payroll taxes. There is no category of costs that comes in for more diverse definition and treatment than general and administrative expense. These costs when allocated to mining, milling, leaching, smelting, etc. may be referred to as indirect mining costs, indirect milling cost, etc.

Indirect costs may range from 30 to 100 percent of direct costs but more commonly are in the 40-60 percent range. Thus, if an operation has a direct mining cost of $0.45 per ton of rock, a 2-to-1 stripping ratio and a direct milling cost of $1.50, the general and administrative costs might be expected to be 40 to 60 percent of $2.85, or $1.14 to $1.71 per ton of ore milled. For an ore with 10 pounds of marketable copper per ton, this represents $0.114 to $0.171 per pound of copper.

Vat or Tank Leaching

Geologic factors that affect the cost of copper recovered by vat leaching include ore and gangue mineralogy and the tendency of the ore to yield fines when mined and crushed.

For an oxide ore assaying 0.65 percent total copper, a good situation would be represented by a high percentage of true chrysocolla or of malachite with a recovery of 70-80 percent of the copper (probably closer to the lower figure), a relatively small percentage of fines to the vats, and a low acid-consuming gangue. The cost of vat leaching under these circumstances could be $1.60-$1.75 per ton of ore leached, resulting in a leaching cost per pound of recovered copper of $0.154-$0.192.

A difficult situation with the same total copper assay would be represented by refractory mineralogy, high fines, and high acid consumption. Recovery could be 45 to 65 percent of the total copper content. The leaching cost could be $3.50 to $4.00 per ton of ore leached, with a leaching cost per pound of copper recovered by leaching of $0.414 to $0.684.

Smelting, Refining, and Freight Costs

For nonintegrated producers the 1976 costs of concentrate freight, smelting, converting, anode casting, anode freight and refining will be in the range of $0.22 to $0.27 per pound of marketable copper in 1977 with the average in the $0.24-$0.26 range.

For integrated producers the costs will be from about $0.140 to about $0.220 per pound.

Financial Costs

A new plant in the western United States to mine and mill 60,000-80,000 tons of ore per day and a smelter to treat the concentrate could cost $500 million or more to engineer, construct, and start. Depending on the amount of debt capital employed, repayment of principal and interest could exceed $75 million in a peak repayment year. If 80,000 tons of ore were milled per day, 350 days per year, with a marketable copper recovery of 10 pounds per ton of ore milled, the principal and interest in such a year would be about $0.27 per pound of marketable copper.

In view of the numbers, it is clear that everything possible must be done to ensure a more-than-adequate available ore supply at and after mill startup. An erroneous conception of the geometry of the top of the ore zone could lead to refinancing $50 to $60 million and add $15 million to the cost of capital. Good grade distribution maps are cheap insurance against such an eventuality. With good level maps and good planning it may be possible to open up the mine to produce at peak capacity without interruption and to high grade to the extent possible without incurring unreasonable costs. This could permit acceleration of debt repayment with savings of tens of millions of dollars.

It should be recalled that a fair return to equity shareholders on their investment is a very real financial cost. In fact the cost of equity capital is normally higher than the cost of debt. The fact that relatively less debt is used in one project than another is not a valid reason for devoting less time and money to careful planning.

What We Can Do

To help keep production costs at an acceptable level the following suggestions are offered. It will be noted that geologists should play a very important role in planning many aspects of a modern porphyry copper operation.

1. From the outset of the drilling program, work toward preparation of bench maps, level by level, that will show the distribution of ore types, ore grades, and waste and geologic structures. Ore type may be defined by a few simple variables: flotation recovery, grindability, pyrite content, and others. Values of such variables may be nearly as important to post to the level maps next to drill-hole intersections as the grade of the drill-hole bench composites. Remember it is not just the orebody and what is within pit limits that affect costs. Structures hundreds of feet behind originally contemplated pit limits may affect pit limits sooner than expected. Prepare two sets of vertical sections, perpendicular to each other, and reconcile them in plan to get good geologic level maps.

2. Many geologic features that influence grade and ore type have steep walls. The only reasonable way to get an accurate picture of the size and orientation of these features is by angle hole drilling. I would not suggest angle hole drilling as a method of reducing total footage needed for an accurate grade estimate. I do suggest it for outlining of waste zones inside the pit.

3. Once a preproduction stripping plan is made, drill some holes behind long ore faces that you are counting on for initial production. There is little excuse for letting a $600 million investment operate at 50 percent of capacity while you catch up on stripping when 10 drill holes would have saved the day.

4. Also recall that you need dumping room. Provide the information on a timely basis for selecting dump areas.

5. Ore type is becoming very important. Not by grade alone does man live. Oxidized or partially oxidized zones of substantial size can penetrate hundreds to more than a thousand feet into chalcocite blankets and chalcopyrite orebodies, leading to substantial quantities of ore with a high acid-soluble copper content. Be alert to the probability (not possibility) of the need to blend for best recovery. Prepare some level maps with ore-type distribution.

TEXTURAL VARIATIONS AND MINERAL ZONING OF THE PILARES BRECCIA PIPE, NACOZARI MINING DISTRICT, SONORA, MEXICO

by

J. A. Thoms [1]

Abstract

The Pilares breccia pipe, located in the Nacozari mining district, about 7 km southeast of Nacozari, Sonora, is the host for the Pilares mine, which produced over 16,600,000 metric tons of ore with an average grade of +2.5% Cu. The well-defined oval-shaped pipe has maximum dimensions of 600 x 300 m and a known vertical extent of 725 m. The major axis trends N. 35° W. The pipe cuts vertically through a sequence of andesitic extrusive and volcaniclastic rocks overlain by latite flow breccia. The volcanic sequence generally strikes N. 45° E. and dips 20°-25° SE. Within the pipe, all volcanic units are thoroughly brecciated, and the andesite-latite contact has been displaced downward as much as 150 m, suggesting collapse during brecciation. Except for a diabase dike, no intrusive rocks are known to occur above the 700 level of the mine. Three general types of brecciation have been observed: (1) tight, (2) open, and (3) tabular. Contacts between the types are gradational, and in some places types 2 and 3 occur together. Up to 30 percent open space developed during brecciation. The entire mass of breccia comprising the pipe has been erratically mineralized; abrupt changes in total sulfide content, pyrite-chalcopyrite ratios, and copper values occur through short intervals. Previously mined, high-grade (+2% Cu) orebodies were localized in nearly continuous vertical ore shoots in the northwest and southeast noses of the oval, in narrow lenses along wall contacts, and in isolated pods ("core ore bodies") in the interior of the pipe. Detailed mapping of channels cut for sampling in rehabilitated mine workings on the 100, 500, 600, and 700 levels has provided new information on sulfide distribution in the interior of the pipe. Zones consisting predominantly of (1) pyrite and (2) chalcopyrite have been defined, as well as mixed pyrite-chalcopyrite zones. A wide belt of specularite extends from wall to wall along the minor axis of the oval on the surface but pinches out rapidly with depth. A symmetrical sulfide mineral zoning pattern is not readily apparent.

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METALLOGENETIC MAP OF SONORA, MEXICO

by

Ariel Echávarri Perez [1]

Abstract

In the recently complete metallogenetic map of Sonora, information about geologic environment and type of deposit of many Sonoran localities is given. Nonmetallic deposits are graphite, anthracite, fluorite, and beryl. The first two, of Triassic age, are of sedimentary origin, commonly forming lenses. Sonora is the leading graphite-producing state. Fluorite is produced from veins in Tertiary volcanic rocks. Beryl in minor quantities is associated with granitic pegmatites. Precious and base metals, including tungsten, are mined from igneous metamorphic zones, epithermal and mesothermal veins, breccia pipes, and low-grade porphyry-type bodies. Gold has been produced from placers.

In the last ten years, porphyry-type deposits have been of most interest. Copper of this kind is found as an extension of the well-known porphyry copper province of the southwestern United States, but it also continues in a belt along the Pacific margin of the Republic of Mexico. In Sonora most copper deposits are found in stocks that intrude calc-alkaline volcanic as well as sedimentary, metamorphic, or even other plutonic rocks. However, in some localities cupolas of great batholiths are mineralized. In these, the shape of the orebodies is disclike and the typical vertical zonation is absent. Intrusive and collapse breccias are relatively common.

Alteration and mineralization patterns are not unlike those of the Arizona deposits. In some areas the potassic, phyllic, and propylitic zones are well exposed, whereas in others only the sericitic-propylitic or the propylitic zones can be observed. The mineralogy is that of the most accepted models. One deposit, however, contains mainly molybdenite. In some breccias scheelite and wolframite have been noted. The age of mineralization is Late Creceous-early Tertiary, during which time the Laramide Revolution produced intense magmatic activity. Recent radiometric studies indicate that the mineralization is progressively younger toward the eastern portion of Sonora. Regional associations between structures and igneous rocks suggest that the deposits formed as a result of subduction of an oceanic plate, probably active until late Oligocene time.

Introduction

The Department of Geology of the University of Sonora, Hermosillo, recently concluded the first step in the elaboration of the metallogenetic map of the state of Sonora. This step consisted of the compilation and partial classification of available information from private and government sources and the careful plotting of hundreds of mines and prospects on the map. In a second step, certain deposits will be selected for the purpose of genetic interpretation. Finally, it is hoped that a reasonable explanation of the processes that produced many commercial and noncommercial deposits can be put in a hypothesis that explains, at least partially, the metallogeny of this part of Mexico.

Physiographically Sonora can be divided into three provinces. The Province of the Barrancas occupies a transitional zone between the Sierra Madre Occidental and the Basin and Range region. Its main characteristic is abrupt topography with very narrow canyons. The Basin and Range province is typical of that of southwestern United States. As is well known, its origin is tectonic. The Desert province in the western part of the state consists of wide valleys interrupted here and there by small hills.

Geologic Environment

The rocks of Sonora range in age from Pre-

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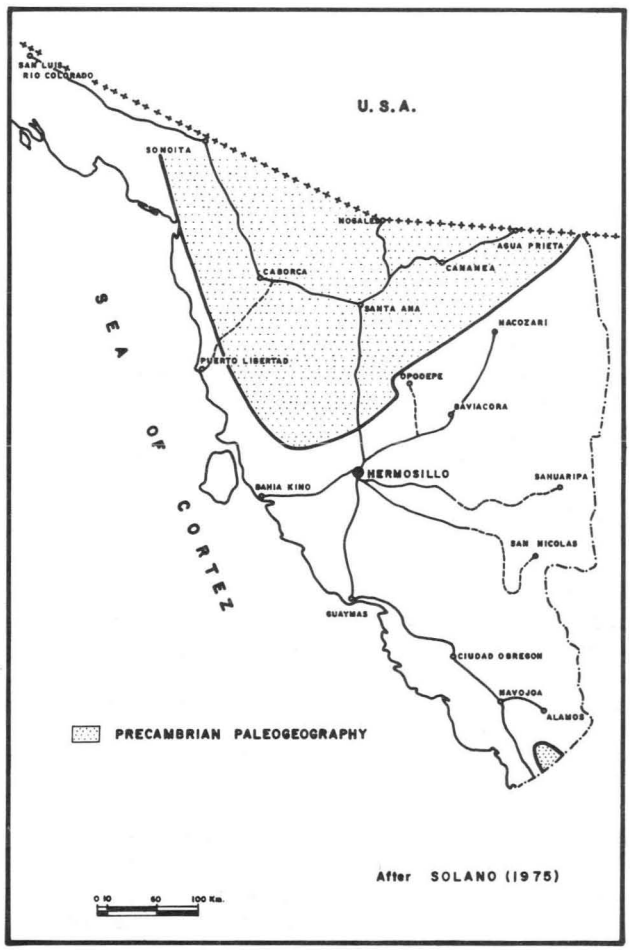

Fig. 1. Precambrian paleogeography, Sonora

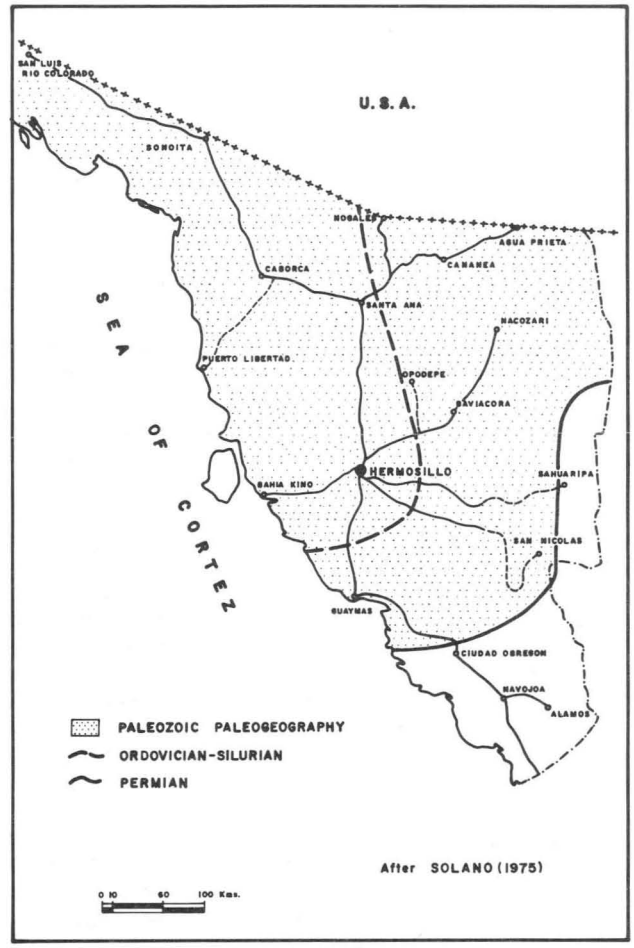

Fig. 2. Paleozoic paleogeography, Sonora

cambrian to Holocene (Fig. 1). The Precambrian rocks (1800-1125 m.y., Anderson and Silver, 1975) traditionally have been divided into "older" and "younger." The former (1800-1600 m.y.) are mainly igneous and metamorphic rocks, which include diorite, quartz monzonite, granodiorite, pegmatite, latite, granulite, amphibolite, metarhyolite, micaschist, and greenschist.

The latter, which rest unconformably on the older Precambrian, consist primarily of quartzite, phyllite, dolomite, and such anorogenic rocks as the Cananea Granite (1440 m.y.), plutonic bodies of quartz monzonite porphyry (1450 m.y.), and granophyric granites (1125 m.y.) (Anderson and Silver, 1975). It is known that the older rocks were perturbed by orogenic movements. However, many authors (Rangin, 1976; Anderson and Silver, 1975) agree that later tectonic movements have erased much of the structural grain of the lower Precambrian rocks.

During Paleozoic time (Fig. 2) the Precambrian craton and most of Sonora were covered by huge thicknesses of calcareous, arenaceous and lutitic sediments. All periods are represented; however, their structure has not been adequately analyzed.

The Mesozoic events are the better known for obvious reasons. Terrigenous and mixed rocks, which include sandstone, shale, and carbonaceous and graphitic shales, were deposited during Late Triassic—Early Jurassic time east of meridian 110°; to the west this sequence grades into sandstone with intercalations of marine shale and limestone (Fig. 3). Minor plutonism and volcanism took place in northwest Sonora (Anderson and Silver, 1975). From Middle Jurassic to Early Cretaceous time the volcanism increased. The erosional products were deposited in two parallel basins separated by a noticeable insular arc. These basins received volcaniclastic sediments, being controlled by a barrier to the east. Beyond the barrier, in the northeast portion of Sonora and in Chihuahua, limestone was deposited (Figs. 4 and 5). Later abundant epicontinental clastic and calcareous sediments were deposited above the volcanic sequence, and Middle

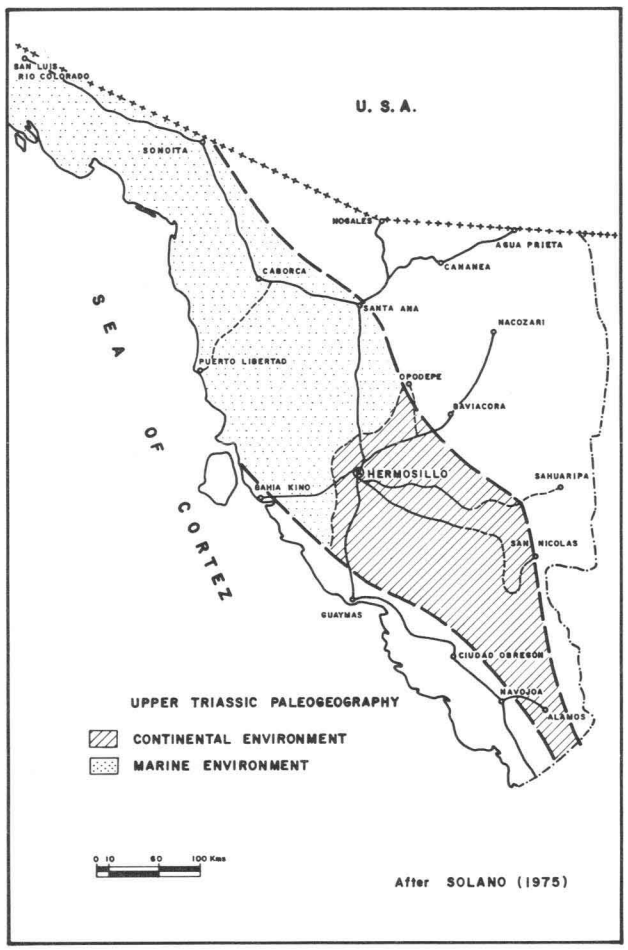

Fig. 3. Upper Triassic paleogeography, Sonora

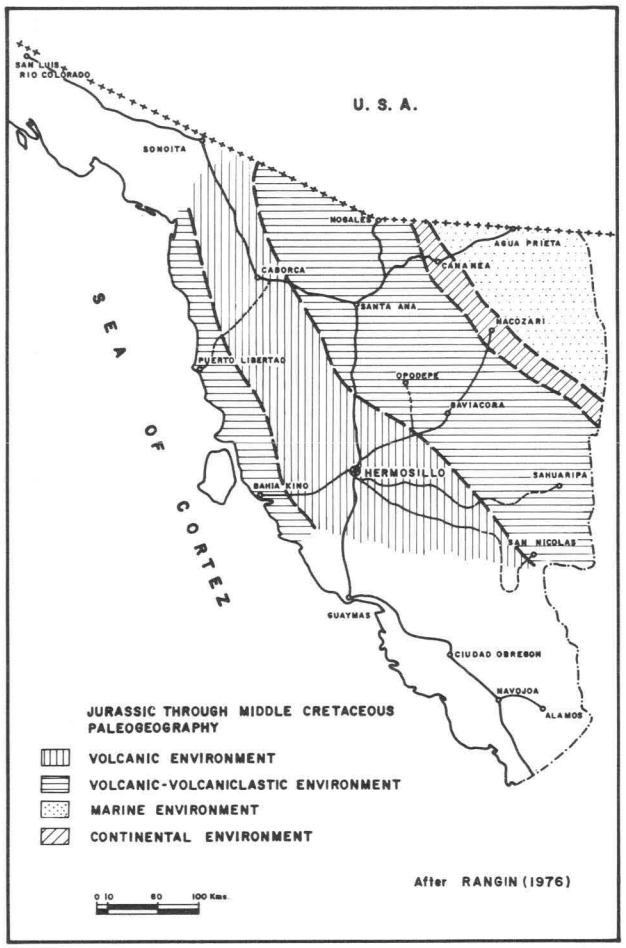

Fig. 4. Jurassic–mid-Cretaceous paleogeography

Cretaceous tectonism affected them, originating folds in northwest-southeast and west-northwest-east-southeast directions (Rangin, 1976). Late Cretaceous time (90 m.y. ago) saw marked intrusion of granodioritic bodies and related volcanism (Anderson and Silver, 1975), minor episodes of sedimentation of lacustrine material associated with gypsum in the western part of the state and sedimentation of detrital material (in which dinosaur bones have found), and extrusion of some volcanic rocks in the eastern portion. The igneous rocks are progressively younger toward the east.

Laramide tectonics resulted in normal and thrust faults. The latter moved Lower Cretaceous rocks above Upper Cretaceous ones with the principal structural directions being northwest and east-southeast (Rangin, 1976). Plutonism and volcanism were especially active processes in the central and eastern part of the state up to the Paleocene (Gastil, 1974). The youngest plutonic rocks of Sonora belong to the Eocene (50 m.y., Solano, 1975). Miocene and Oligocene andesitic, rhyodacitic, and rhyolitic tuffs are widespread. The Pliocene epoch was a time of great block faulting and some extrusion of basalts. These were rapidly covered by alluvial sediments. Pleistocene basaltic volcanism covered small, isolated areas (Fig. 6).

Nonmetallic Minerals

Fluorite, coal, and graphite are the most important nonmetallic minerals of Sonora (Fig. 7). Coal and graphite are found in lutitic horizons of the Upper Triassic Barranca Formation. Sonora is an important world producer of graphite, which occurs in beds approximately one meter thick. The coal is of anthracitic type. Both coal and graphite originated by dynamic and thermal metamorphism. There are many fluorite manifestations in Sonora, but only two are of economic importance: Esqueda in the northern part of the state and Santa Rosalía in the eastern portion. Both deposits are in veins located in premineral faults that put in contact differing volcanic country rocks such as andesite and rhyolite. Vein thicknesses reach some meters in both deposits,

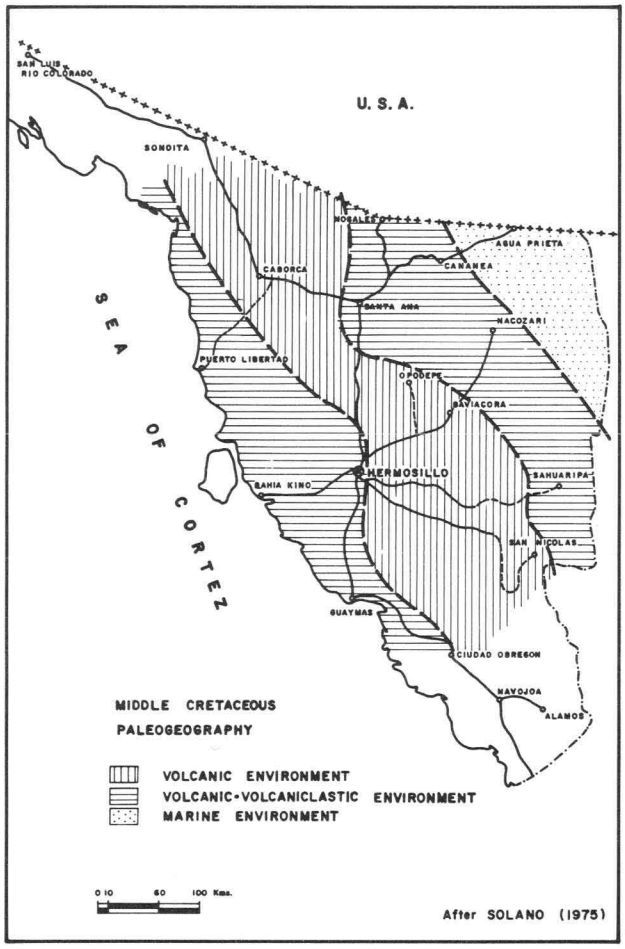

Fig. 5. Mid-Cretaceous paleogeography

but grade is better at Esqueda. Gangue minerals are barite, quartz, and calcite. Minor fluorite associated with granitic rocks is found elsewhere in the state. Beryllium is found in pegmatites in the Aconchi batholith, but no economic significance is attached to this occurrence.

Metallic Minerals

The metallic minerals of Sonora are numerous and important. They have been so in the past, and their future is bright.

Tungsten, Iron, and Radioactive Minerals

Tungsten has been an important element in the economy of Sonora. It can be found in granitic pegmatites or in plutonic bodies where it is of minor interest. Of major importance are the igneous metamorphic deposits, such as Baviacora. Other interesting occurrences are as a by-product of igneous metamorphic zinc-copper deposits and more rarely associated with the collapse breccias of the porphyry coppers. The common mineral is scheelite, but wolframite has been noted in some breccias. A common assemblage in the breccias is scheelite-chalcopyrite-pyrite-molybdenite. The last three minerals are also found in small quantities in the metasomatic bodies. The mineralization is of Laramide age.

Only one contact-metamorphic iron deposit has been exploited at El Volcán (Fig. 9). The known deposits of radioactive minerals are of several origins. In some, the ores are located in oxidized zones (San Antonio de la Huerta, El Picacho, Arizpe), whereas others are concentrated with hypogene sulfides (Noche Buena, El Rosario). Mineralization can also be in veins, in skarns, sedimentary beds, breccias, and fracture zones in granitic rocks. The principal minerals are pitchblende, kasolite, uranophane, uranopilite, bassetite, johannite, autunite, iriginite, torbernite, and metatorbernite. The age of ore deposition apparently is Cambrian in the sediments, Laramide in the plutonic and contact metamorphic bodies, and middle Cenozoic in the vein deposits (García y Barragan, 1976).

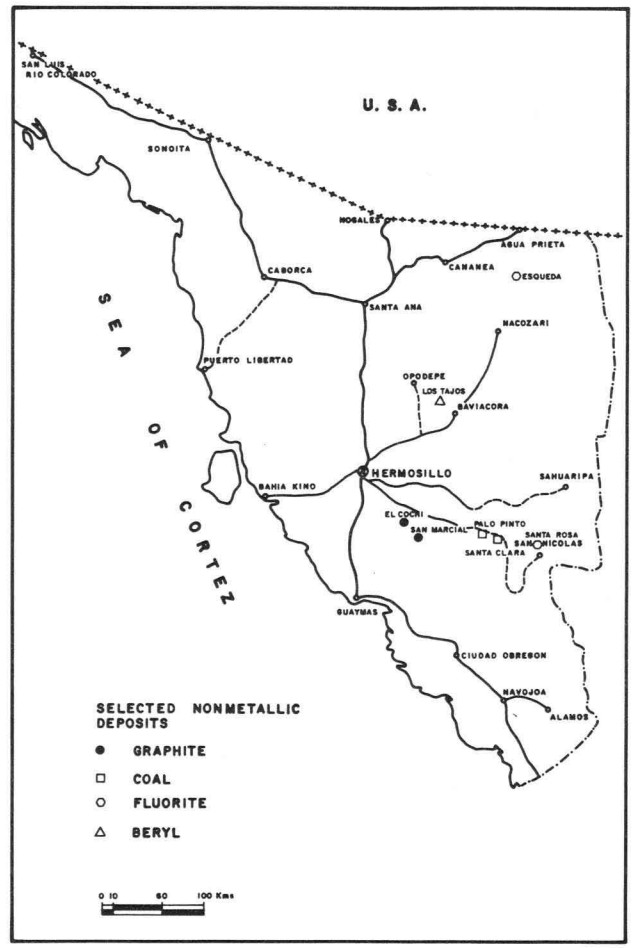

Fig. 7. Selected nonmetallic deposits, Sonora

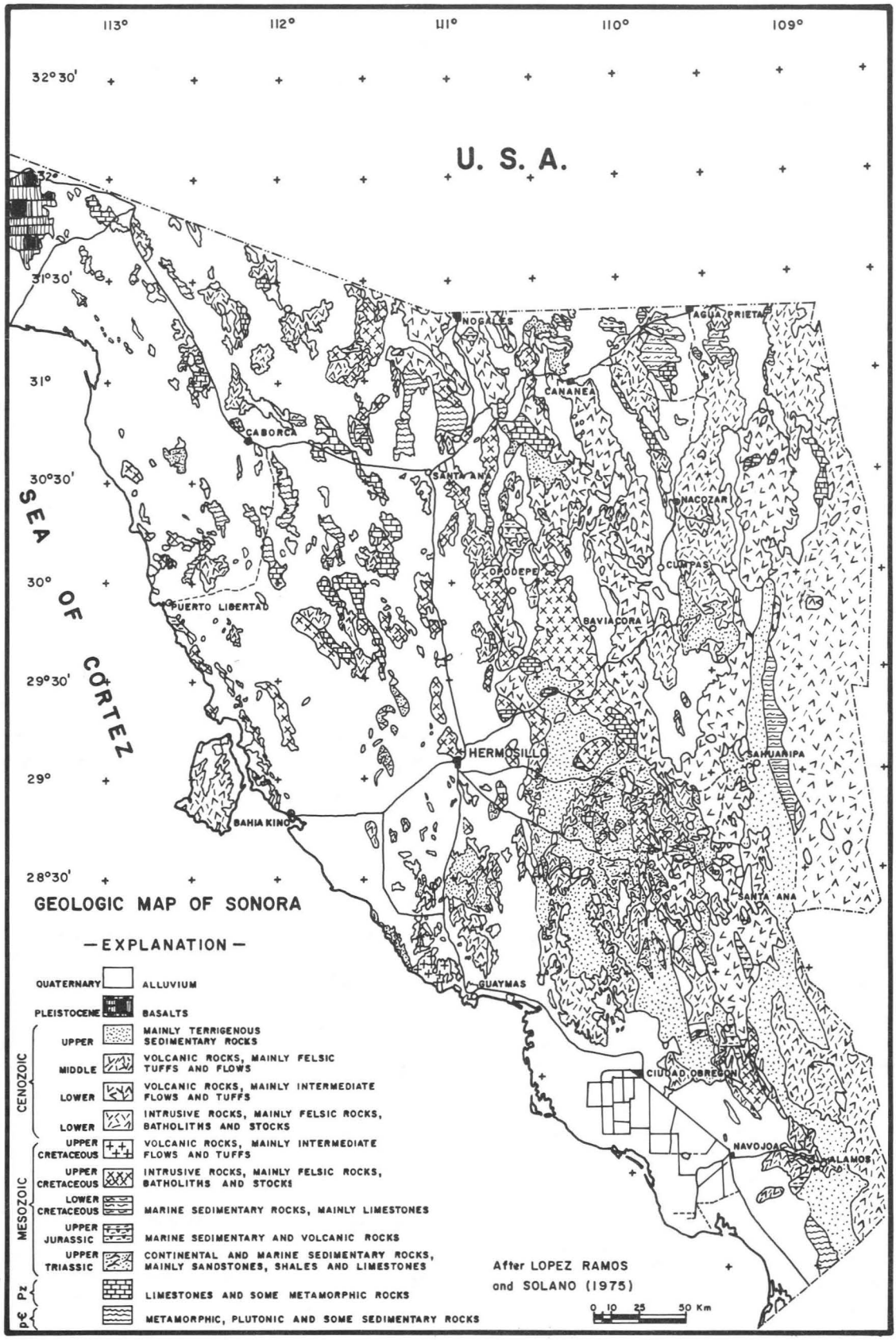

Fig. 6. Geologic map of Sonora—After López Ramos and Solano (1975)

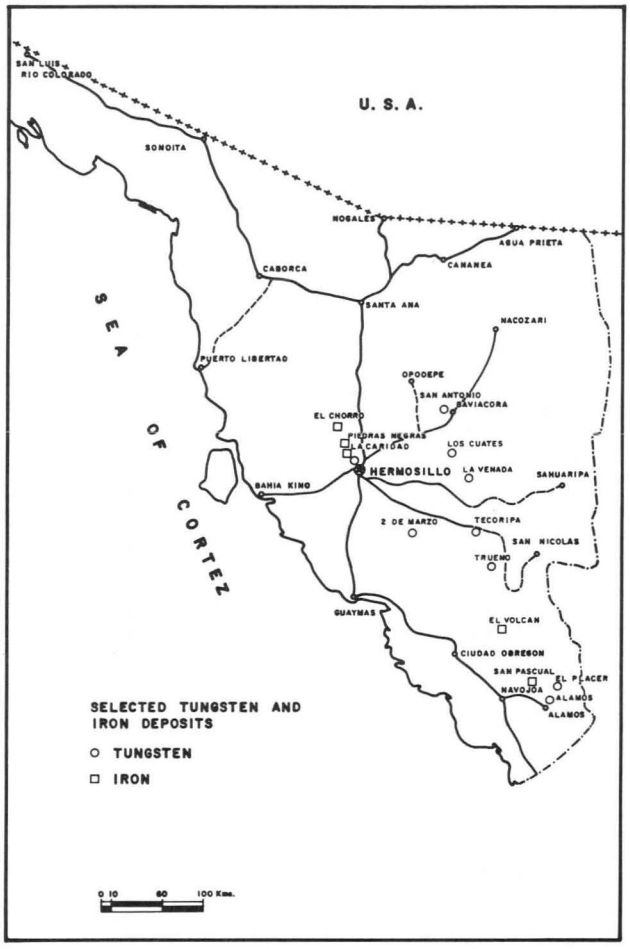

Fig. 8. Selected tungsten and iron deposits

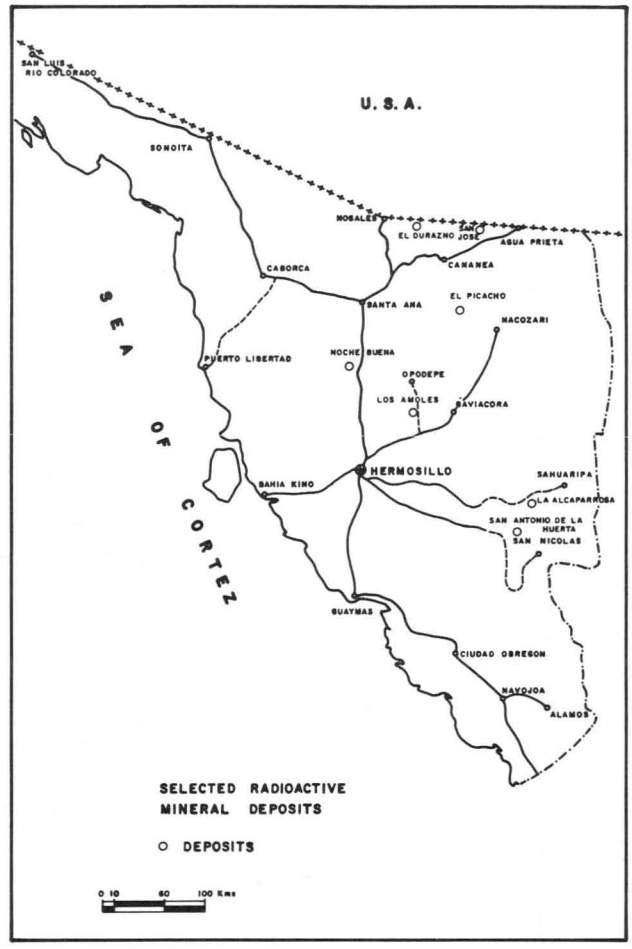

Fig. 9. Selected radioactive mineral deposits

Zinc and Lead (Fig. 10)

These elements are found in igneous metamorphic deposits or in veins. With the latter, silver can be of important value. There appear to be two ages of mineralization. The metasomatic ores are commonly associated with hypabyssal granitic rocks which contain little copper and pyrite and are of Laramide age. Here marmatite, chalcopyrite, pyrite, occasional pyrrhotite and magnetite, and little galena with little silver are common and represent the greatest reserves in the state. Examples of these deposits are Cananea, San Felipe, El Tecolote, and Cabullona. The host rocks are skarns with garnet, pyroxene, and scapolite derived from limestones of various ages.

The vein deposits are enclosed by sedimentary rocks of various ages or by volcanic rocks of middle Cenozoic age. Sphalerite and galena with silver values and minor chalcopyrite are dominant in the lower parts of the veins but gradually disappear upward into quartz-rich rocks with an increase in gold and silver grades. Examples are Lampazos and San Javier.

Silver and Gold (Fig. 11)

Silver and gold are commonly associated with the base metals. The common minerals are argentite, polybasite, and pyrargyrite-proustite. Very little information is available on gold mineralogy. Principal silver vein deposits are El Tigre, Las Chispas, La Colorada, Lampazos, and San Javier (Wisser, 1966). Gold also occurs as small deposits in quartz-rich Precambrian and Paleozoic metamorphic rocks on the western portion of the state. Placer deposits derived from the above are minor.

Copper and Molybdenum (Fig. 12)

Two types of copper and molybdenum deposits occur in Sonora: those in veins, which are small and of little importance, and the large disseminated porphyry type. The latter are an extension of the well-known porphyry copper province of the southwestern United States.

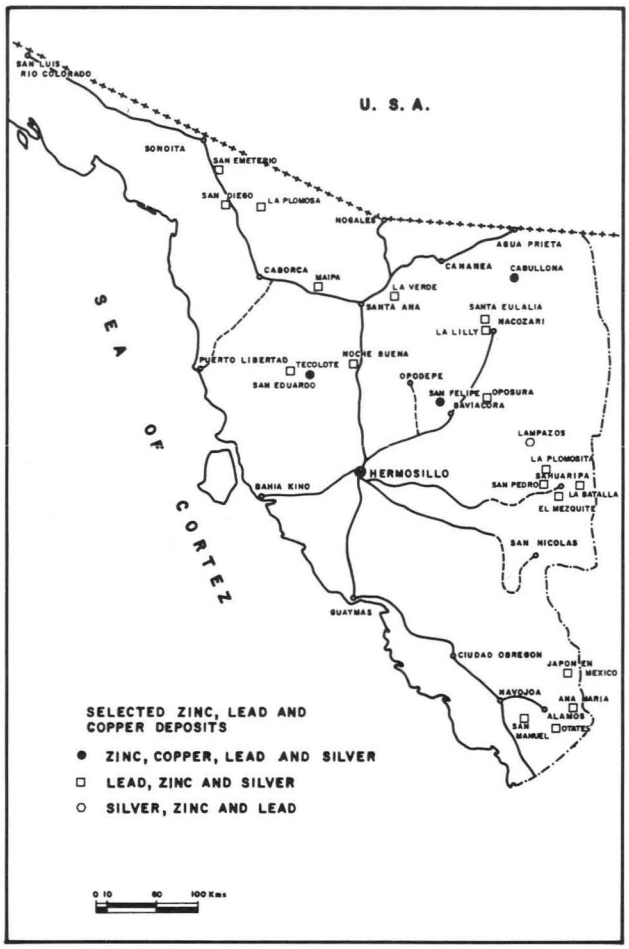

Fig. 10. Selected Zn-Pb-Cu deposits

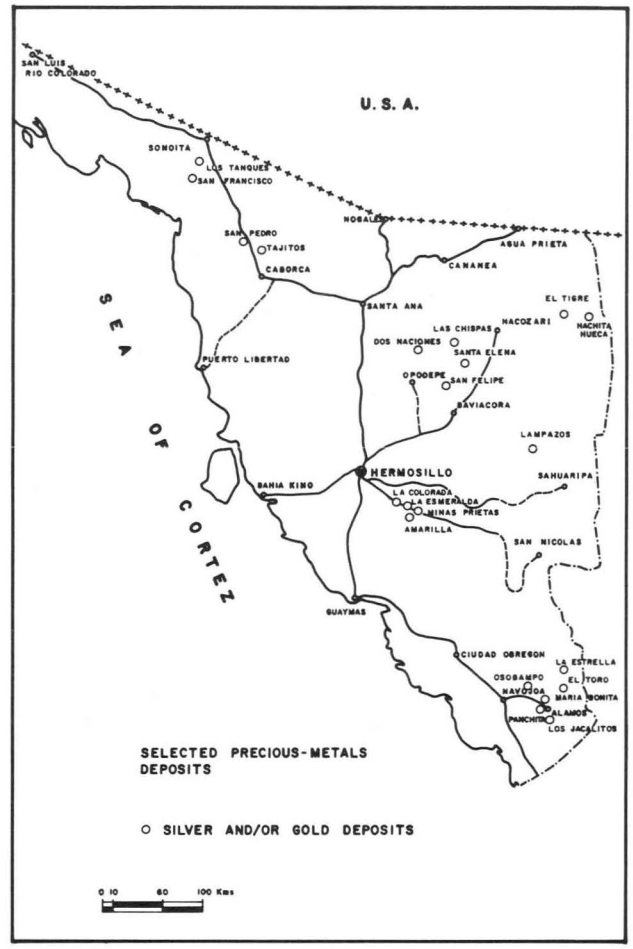

Fig. 11. Selected precious metals deposits

Three classifications are recognized (Sillitoe, 1975):

1. Stockwork deposits with a columnar shape and alteration-mineralization in the form of envelopes. They are associated with stocks and can have breccia pipes related to them.

2. Plutonic roof rock deposits. These are large masses in which the alteration and mineralization are semiplanar or discoid. They are restricted mainly to the roof rocks but many penetrate to the cupola of the batholiths.

3. Breccia pipe deposits, isolated or in groups, intrusive or collapse in origin. Most mineralization is copper-molybdenum; however, Meztli is almost exclusively a molybdenum deposit whereas San Antonio de la Huerta is copper only.

Associated intrusive rocks of most deposits range from granodiorite to quartz monzonite. Only La Florida and San Antonio de la Huerta are in dioritic to andesitic rocks. The La Caridad and Cananea deposits were formed as a result of hydrothermal processes related to multiple porphyry intrusions. Textures, degree of alteration, and mineralization reveal repeated periods of magmatism. San Antonio de la Huerta and Piedras Verdes are good examples of deposits in which sedimentary rocks were either totally or partially the hosts. Most of the deposits, however, were emplaced within volcanic calc-alkaline rocks of andesitic composition (Solano, 1975). A few, including La Caridad, Fortuna de Cobre, and Meztli (El Creston), are hosted by altered plutonic rocks. Aurora and Batamote formed at the roofs of intrusive rocks, which show little or no alteration. The collapse breccia pipes are hosted by batholithic rocks (Los Verdes) or by volcanic rocks (Cobre Rico, Washington, and Pilares). There is no apparent intrusive body in the vicinity of the latter three; Los Verdes could represent the root of a collapse breccia pipe.

Two types of breccias are recognized: those formed by collapse with or without as-

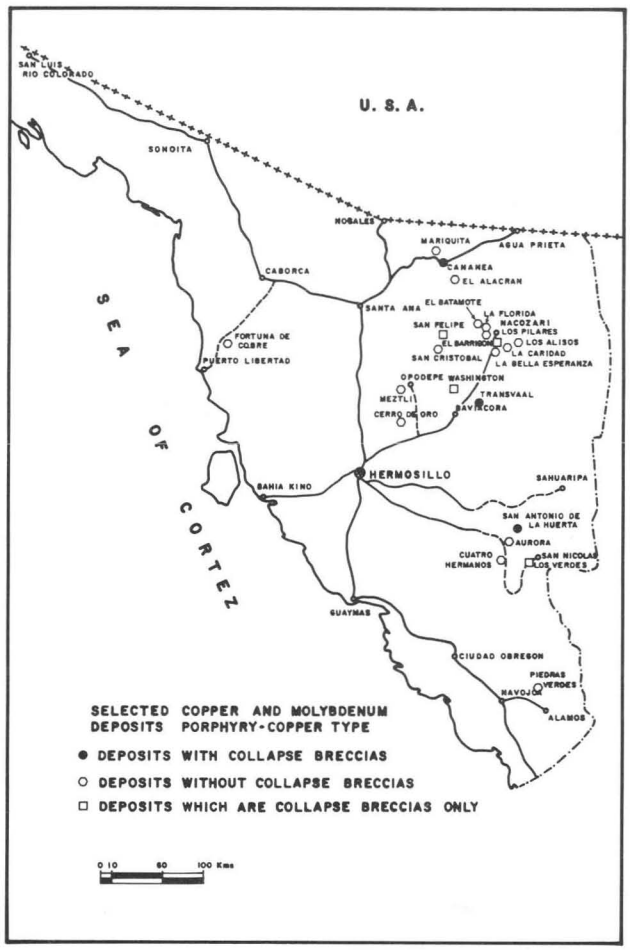

Fig. 12. Selected Cu-Mo porphyry type deposits

sociated stockwork mineralization and those of hydrothermal intrusive origin that are found within the mineralized bodies. Collapse breccias generally have an elliptic form with a rather prominent long axis, thus presenting a columnar shape. Their contacts with the non-brecciated zones are sharp. The fragments are commonly angular and form small, planar flakes in agglomerations near the walls or around rounded fragments. Their size is extremely variable, ranging from a few centimeters to some meters in maximum diameter. After brecciation, the resulting pore spaces were filled with either quartz and sulfides or quartz and tourmaline.

The intrusive breccias, dike, pipe, or sill-like in shape, are intimately associated with stockwork bodies. Generally they are smaller than the collapse breccias and more numerous. Transvaal, La Caridad, Cuatro Hermanos, and Cananea are typical localities. Commonly, the fragments are rounded and fragments of several rock types can be found. Characteristically, the cementing material is rock flour and sericitic alteration is dominant. At La Caridad, and perhaps in Cananea, intrusive breccias are important ore controls. In many places, the breccias are the deposits themselves (Los Verdes, Pilares, Washington, San Antonio de la Huerta, and elsewhere in Mexico). In some areas the two types of breccias can be found (Transvaal, Cananea, and even La Caridad).

Even though the Mexican porphyry belt has notable variants, the Sonora localities validly conform to the alteration-mineralization model of Lowell and Guilbert (1970). Fortuna de Cobre, Meztli, El Alacran, and Transvaal exhibit a central potassic zone that grades outward into a sericitic zone and further into a propylitic zone. Meztli (El Creston) has good molybdenum values in the potassic-sericitic interface. At La Bella Esperanza and Cananea (where superimposed alteration zones can be observed inside a vast and early potassic zone; Sillitoe, 1975), sericitic and propylitic alteration are of note. In both Cananea and La Caridad there exists a potassic zone, thus confirming the validity of the Lowell and Guilbert model. Piedras Verdes, Lucia, Aurora, Batamote, Mariquita, and Cuatro Hermanos, which are in roof pendants, have a discoid shape with sericitic-propylitic alteration. At Cuatro Hermanos the alteration is shallow, thus offering the possibility of a potassic zone at depth.

All intrusive breccias are located within either the sericitic or propylitic zones with the exception of the Transvaal breccia, which is in the potassic zone. The collapse breccias, on the other hand, can be in the potassic zone (San Judas, La Verde, Transvaal, and partially Los Verdes) or in the potassic zone that grades into sericitic and further into propylitic zones (Los Verdes and Washington) or in the sericitic-propylitic zone further enveloped by a propylitic zone (Pilares and Cobre Rico). San Antonio de la Huerta breccia is silicified. Tourmaline and alunite are common in some breccias. In collapse breccias the common mineral assemblage is pyrite-chalcopyrite-molybdenite-scheelite-wolframite.

Supergene enrichment is not noticeable in most deposits; major exceptions are Cananea, San Antonio de la Huerta, Washington, Cobre Rico, and Los Verdes. At San Antonio, copper silicates and carbonates are exposed at the surface.

Most porphyry copper deposits of Sonora are of Laramide age (Livingston, 1974) and are related to batholithic rocks whose ages range from 90 m.y. in western Sonora to 53 m.y. at Aurora (Fig. 13). As far as the genesis is concerned, a plate tectonic environ-

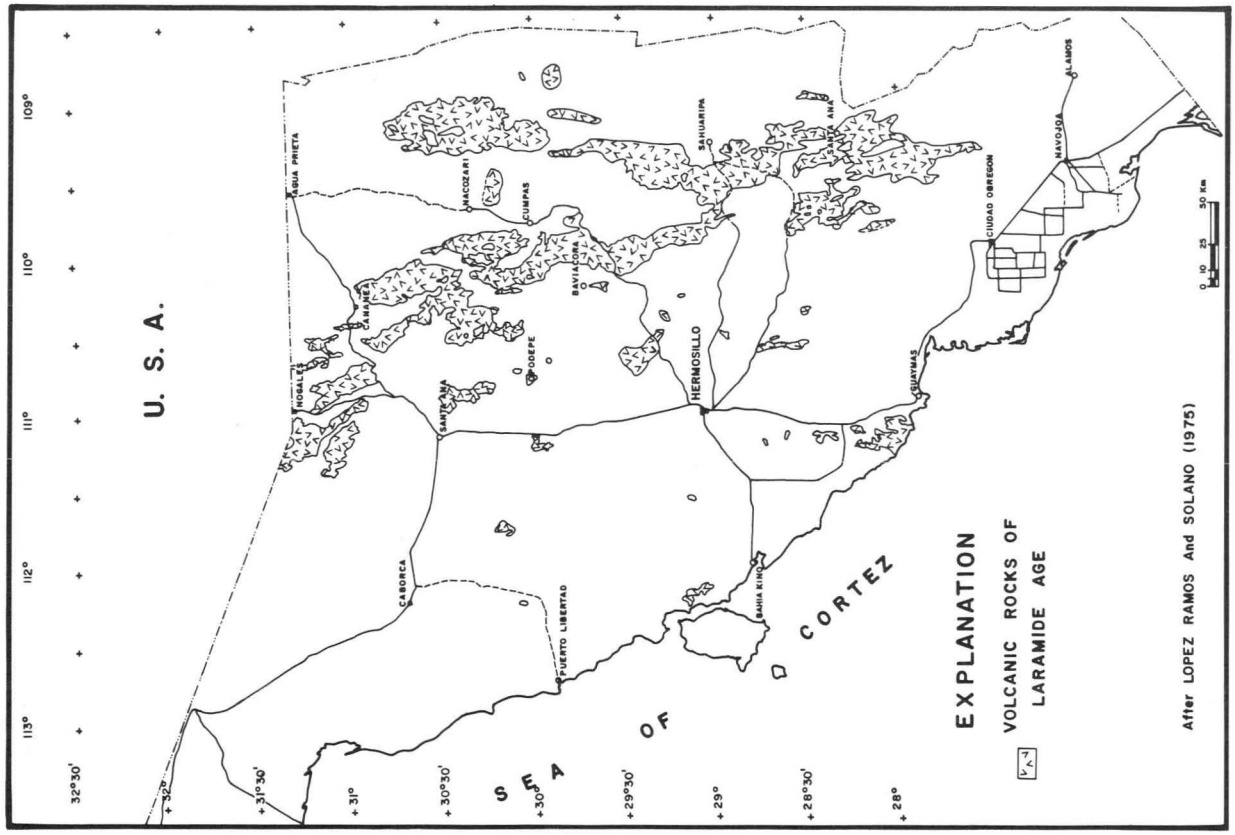

Fig. 14. Volcanic rocks of Laramide age

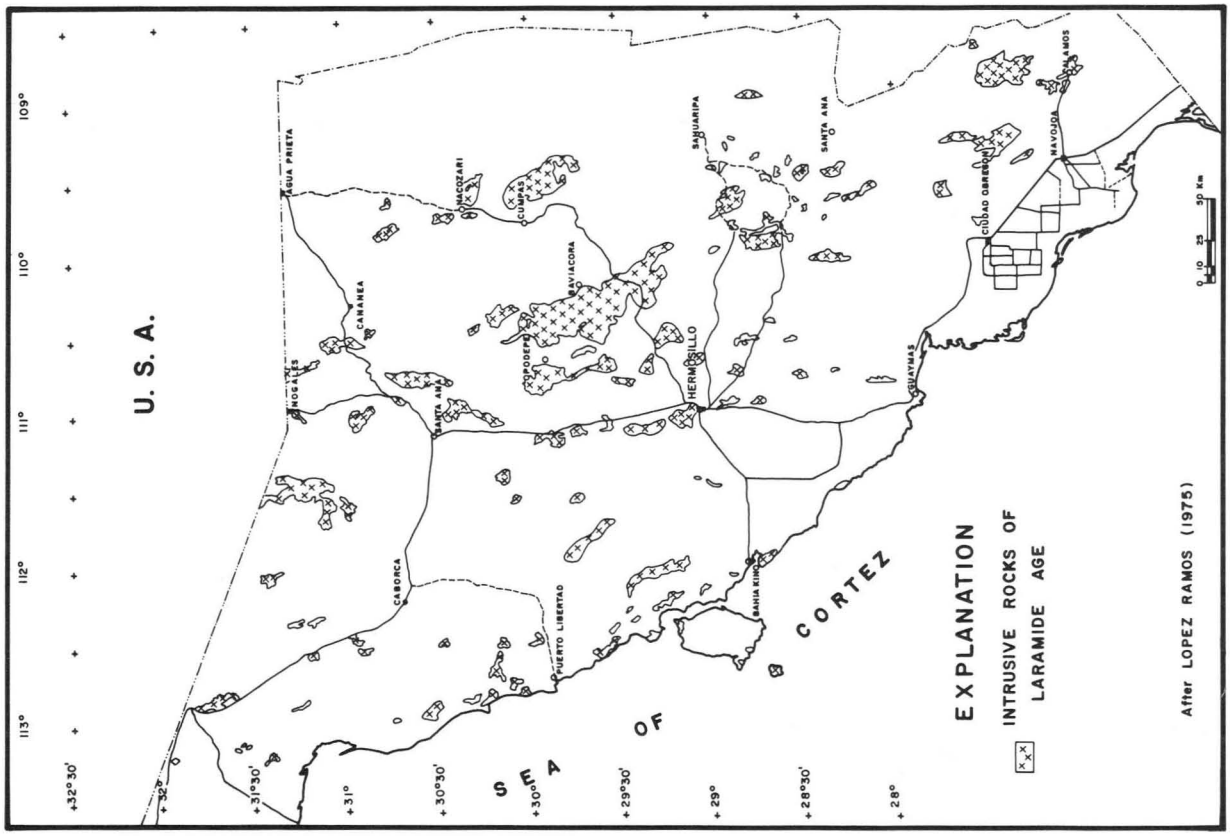

Fig. 13. Intrusive rocks of Laramide age

ment similar to that proposed for Canada and the rest of the Pacific Coast seems to have been present when the Sonora ores formed (Solano, 1975; Sillitoe, 1975; Farías and Peña L., 1975). Gastil (1975) also explained the formation of the batholithic belt of Baja California and Sonora as a result of the partial fusion of a subduction plate during the Mesozoic–early Cenozoic interval (Fig. 14). The intimate relation between batholiths and orebodies and the fact that their ages diminish progressively toward the east seem to support the plate tectonic view; so does the calc-alkaline composition of the associated and widespread volcanic rocks.

Antimony and Manganese

Antimony and manganese mineralization has been reported, but the extent of the deposits is not known.

Acknowledgment

I wish to thank Mrs. Jerjes Pantoja Alor, Guillermo P. Salas, and Moises Martinez for their valuable help. Servicios Industriales Peñoles, Industrial Minera México, Instituto Nacional de Energía Nuclear, and Minera Trion were most kind in lending unpublished data. Mrs. Guillermo A. Salas, Oscar Saitz, and José Dewar helped with the translation into English and with the drafting.

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LATE CENOZOIC VOLCANISM AND METALLOGENESIS OVER AN ACTIVE BENIOFF ZONE IN CHIAPAS, MEXICO [1]

by

Paul E. Damon [2] and Enrique Montesinos [3]

Abstract

Chiapas, Mexico is a critical area for plate tectonic phenomena. The southeast part of the state, in the region of Motozintla, marks the juncture of three plates: the American, Cocos, and Caribbean plates. The Central (Middle) American trench strikes parallel to the coastline and to most of the large-scale geological features of Chiapas such as the Sierra Madre de Chiapas, the Central Depression, and the folded ridge and valley province of northeastern Chiapas.

The offshore trench and inland Chiapas are regions of intense seismicity. There is a distinct tendency for fewer but deeper and more intense earthquakes proceeding from the trench to inland Chiapas. This pattern of seismicity is similar to that of other Benioff zones and demonstrates that the Cocos plate is continuing to subduct under Chiapas.

The major mineral deposits of Chiapas are genetically associated with Cenozoic plutons. One set of plutons has been shown by K-Ar dating to be middle to late Miocene in age. These plutons intrude an ancient Paleozoic batholithic terrain within the Chiapas Massif. This set of plutons lies along an abandoned segment of the Miocene Central American-Mexican volcanic arcs.

The second set of plutons is clearly associated with a belt of calc-alkalic, andesitic to dacitic stratovolcanos of Pliocene and Pleistocene age. The volcano El Chichón in that belt contains an active solfatara field. Others still retain much of their primary structure. This belt is referred to as the modern Chiapanecan volcanic arc.

The rate of erosion required to expose the mineral deposits below the tops of the stratovolcanos, according to the model of Sillitoe (1973), is from 300 m/m.y. to 900 m/m.y.

Prior to 9 m.y. ago, the ancestral Mexican volcanic arc was probably continuous to Cape Corrientes. Between 9 and 3 m.y. ago, reorganization of the subducting Cocos plate resulted in a volcanic arc, which is convex to the north. A magma gap exists within the Central Depression of Chiapas.

We conclude that continuing ore genesis in Chiapas is associated with subduction of the Cocos plate. The ore deposits are the roots of calc-alkalic stratovolcanos. Both the ancestral Miocene Central American-Mexican arcs and the modern arc are prime targets for ore deposits of Neogene age.

Plate Tectonic Setting of Chiapas

This work is part of a cooperative investigation of the age and genesis of the Mesozoic-Cenozoic metallogenetic provinces of the Republic of Mexico by the Consejo de Recursos Minerales and the Laboratory of Isotope Geochemistry of The University of Arizona. Most of the field work was done during the winters of 1974 and 1975. Chiapas was selected for an early phase of the investigation because of its unique plate tectonic setting (Fig. 1). It is located near the junction of three plates:

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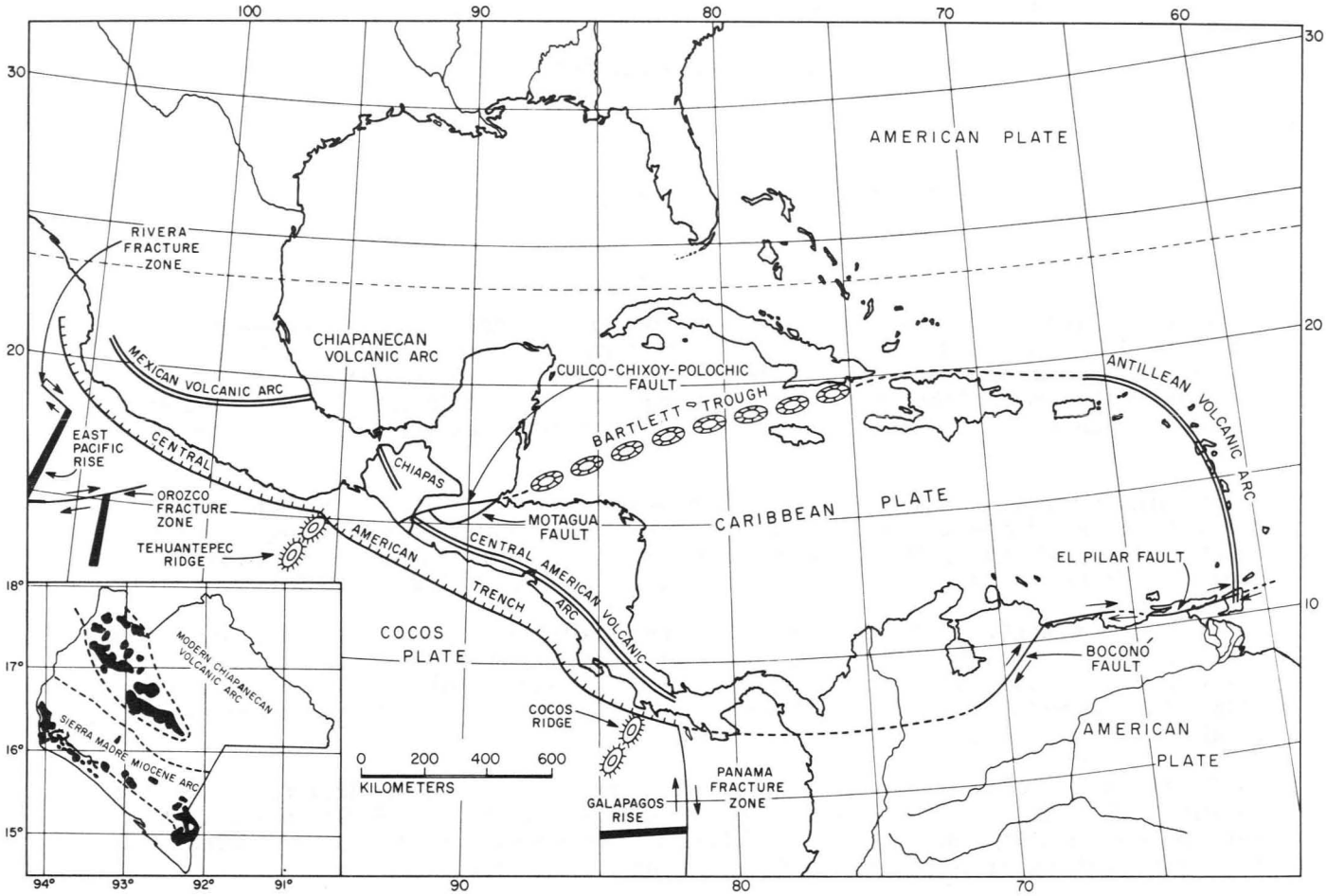

Fig. 1. Plate tectonic sketch map of the Cocos, Caribbean, and American plates from Cape Corrientes to Venezuela. Data for this figure was obtained from Chase, Menard, and Mammerick (1970), Fisher (1961), Herron (1972), Molnar and Sykes (1969), Muehlberger and Ritchie (1975), Schubert and Sifontes (1970), Schubert (1974), and Shor and Fisher (1961).

the American, the Caribbean, and the Cocos plates. The Cuilco-Chixoy-Polochic fault forms the present boundary between the Caribbean and American plates in southeastern Chiapas and Guatemala (Kesler, 1971; Muehlberger and Ritchie, 1975). The Central (Middle) American trench forms the boundary between these plates and the Cocos plate roughly paralleling the Central American shoreline.

The offshore trench and inland Chiapas are regions of intense seismicity (Fig. 2). There is a distinct tendency for fewer but deeper and more intense earthquakes proceeding from the trench to inland Chiapas. This pattern of seismicity is similar to that of other Benioff zones and demonstrates that the Cocos plate is continuing to subduct under Chiapas.

Physiographic Provinces of Chiapas

Chiapas can be divided for convenience into seven physiographic provinces (Fig. 3): Province 1 consists of the Pacific coastal plain. Province 2 is the Sierra Madre del Sur of Chiapas, which will be referred to as the Chiapas Massif. Province 3 is the Central Depression, a grabenlike depression through which the Río Grijalva flows. Province 4 comprises the high plains surrounding San Cristóbal de las Casas. Province 5 is a valley and ridge province, which decreases in elevation to the northeast as the basin of the Río Usumacinta is approached. Province 6 is the northern mountain province. The eastern part of this province contains northwest-trending valleys and ridges which are a continuation of the less rugged valley and ridge region within Province 5. The folded sedimentary rocks in the western part of Province 6 have been disrupted by the differential vertical tectonics resulting from igneous intrusions and the presence of stratovolcanos. Province 7 is part of the Gulf of Mexico coastal plain.

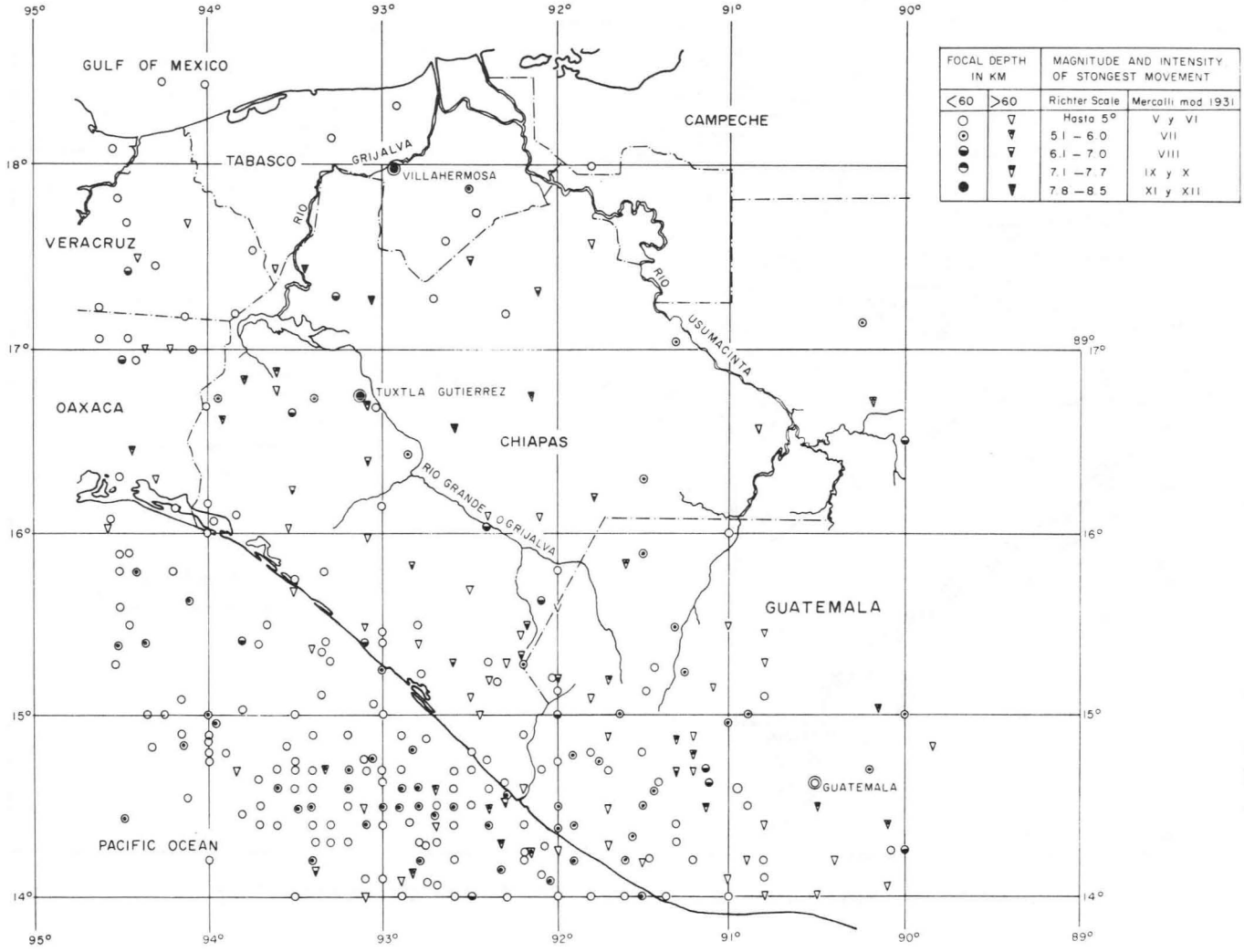

Fig. 2. Seismic map of the state of Chiapas—after Figueroa-A. (1973)

Résumé of the Geology of Chiapas

A primitive terrain of metamorphic rocks has been recognized in Chiapas since before the end of the 19th century (Aguilera and Ordóñez, 1893). More recently, Pantoja-Alor and others (1974) have demonstrated that at least some of these metamorphic rocks within the Sierra Madre del Sur of Chiapas (Province 2, Fig. 3) are late Precambrian in age approximately correlative with the Oaxaqueña orogeny of Fries, Schmitter, Damon, and Livingston (1962). This orogenic belt extends in an arc from Guatemala through southwestern Chiapas, central Oaxaca, northeastern Guerrero, Puebla, and Hidalgo to western Tamaulipas (Fries, Schmitter, Damon, Livingston, and Erickson, 1962; Fries and others, 1974). Fries, Schmitter, Damon, and Livingston (1962) correlate the Oaxaqueña orogeny with the Grenville orogeny in Canada. These rocks have not been differentiated from later metamorphic rocks on the state map of Chiapas and are included in Figure 4 with Paleozoic metamorphic and intrusive rocks.

These Paleozoic igneous intrusions and metamorphic rocks range in age from Cambrian through Permian (Damon and Salas, 1975). In the Sierra Madre del Sur of Chiapas, the final event of the Paleozoic was the intrusion of a late Permian batholithic complex, which intrudes the older metamorphic rocks and the Santa Rosa Formation of Permian age.

The Santa Rosa Formation consists predominantly of limestones and dolomites with intercalated carbonaceous beds. These beds were deposited in the Paleozoic Guatemalan geosyncline, which forms a great arc from northeast to northwest, convex toward the south. This geosyncline crossed Belize, much of Guatemala, and virtually all of Chiapas.

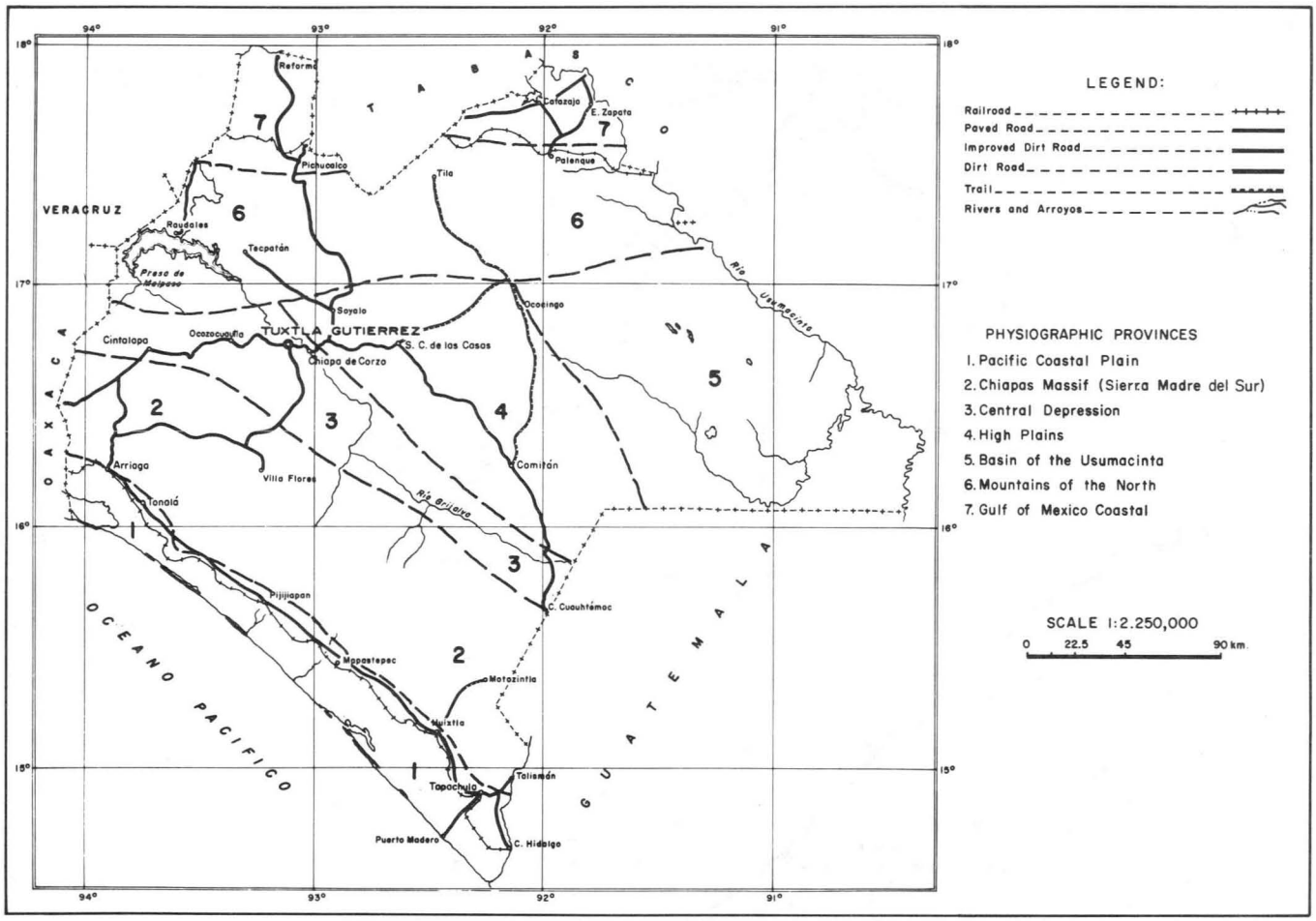

Fig. 3. The physiographic provinces of Chiapas—after Böse (1905)

Following the deposition of sediments in the Guatemalan geosyncline, a large basin was the locus of salt deposition, the so-called Isthmus Salt Basin of Late Jurassic age or post-Callovian–pre-late Oxfordian according to Viniegra-O. (1971). This salt basin occupied most of Chiapas excepting the Sierra Madre del Sur and Pacific coastal plain. In northern Chiapas, salt deposition continued into latest Jurassic (Kimmeridgian-Tithonian) time according to Viniegra-O. (1971). The salt deposits are overlain toward the Chiapas Massif by the red beds (Lechos Rojos) of the Todos Santos Formation. On the state geologic map of Chiapas (Fig. 4), the Todos Santos Formation is referred to as Triassic-Jurassic in age; however, according to Viniegra-O. (1971), this formation must be Late Jurassic and Early Cretaceous in age. Some geologists refer to the Early Cretaceous continental red beds intertongued with marine limestones as the San Ricardo Formation (Richards, 1963). We examined the Todos Santos red beds east of Cintalapa. The formation there consists of aeolian cross-bedded sandstones and cobble conglomerates containing quartz, granitic debris, and abundant volcanic rock grains and cobbles. In one place, we found a cobble of red-bed sandstone within a Todos Santos red-bed conglomerate. The general aspect was that of debris from the unroofing of the ancestral Chiapas Massif (Province 2, Fig. 3). The abundance of volcanic rock fragments indicates that erosion of the Chiapas Massif had not proceeded to a great depth at the time of deposition of the Todos Santos Formation. From the outcrop pattern (Fig. 4) one can surmise that debris from unroofing of the massif was distributed to a basin lying to the northeast.

Marine conditions prevailed throughout Chiapas following the deposition of the San Ricardo Formation. Limestone and dolomites are most abundant with lesser amounts of chert, shale, and sandstone. Occasionally, deposition of marine sediments was interrupted by formation of soils, some of which were lateritic. During this time, Chiapas was part of the Mexican geosyncline (Kay, 1951).

Fig. 4. A simplified geologic map of Chiapas compiled from Petroleos Mexicanos and Consejo de Recursos Minerales sources

During the early Cenozoic, marine deposition retreated to the northeast. By late Eocene time, the southwestern half of Chiapas was a land area and streams were carrying cobbles of schist, granite, and quartzite to the northeast beyond what is now the Central Depression of Chiapas (Province 3, Fig. 3). These streams deposited the conglomerates that are included within the El Bosque Formation.

Marine conditions prevailed in northern Chiapas through the Oligocene epoch. However, the seas gradually retreated to the north toward the Gulf of Mexico. Terrestrial conditions prevailed from Miocene time to the present.

The state geologic map of Chiapas (Fig. 4) shows two episodes of igneous activity: an early Cenozoic episode of dioritic, granodioritic, and quartz monzonitic intrusions and a late Cenozoic episode of volcanic activity. We will demonstrate in this paper that there are two episodes of igneous activity, but both are Neogene in age rather than separated into Paleogene intrusive and Neogene volcanic episodes.

K-Ar Dating Techniques

The K-Ar dating method requires precise, accurate determinations of K and ^{40}Ar (Dalrymple and Lanphere, 1969). In the Laboratory of Isotope Geochemistry, K was determined by atomic absorption spectrophotometry. The solution used contained 0.1 g of the sample as sulfate in 200 ml of aqueous solution containing 800 ppm Li and 1000 ppm Na. Two aliquots were measured for each sample. The atomic absorption spectrometer used was a Perkin-Elmer 403, single beam instrument. A 30 lb-60 lb acetylene-air flame was used with the wavelength dial set at 3827 Å (3-slot burner head in parallel position, slit 4, filter in).

Molybdenum crucibles were used for the radio frequency induction heating to fuse the sample to release argon for analysis. The molybdenum crucible was suspended by a platinum wire and carefully centered within a 90-mm air-cooled pyrex fusion envelope. Four samples were mounted in the fusion system, and the system was baked over the weekend at 270°C. The system was also baked overnight after every fusion. In addition to the usual titanium foil gettering and conversion of hydrogen to water over CuO, a Zr-Al appendage pump provided a final purification step that insures very pure argon for mass spectrometric analysis.

Argon isotopes were analyzed on either a Nier-type 15.2 cm radius, 60° sector field mass spectrometer with magnetic sweeping or an MS-10, 5.1 cm, 180° mass spectrometer with electrostatic sweeping. Two analyses per fusion were made in the static mode.

For young samples, for example, samples of Pleistocene age, the standard error was determined primarily by the atmospheric argon contamination. The standard deviation for a sample with negligible air argon is 2.3%, 15% with 90% air argon, and 100% with 98.4% air argon.

All dates were calculated with the following decay constants:

$$\lambda_e = 0.581 \times 10^{-10}\ yr^{-1}$$

$$\lambda_\beta = 4.963 \times 10^{-10}\ yr^{-1}$$

$$\lambda = 5.544 \times 10^{-10}\ yr^{-1}$$

$$^{40}K/K = 1.167 \times 10^{-4} \text{ atomic ratio}$$

Age and Genesis of Cenozoic Igneous Rocks in Chiapas, Including the Southern Oaxaca Border Region

There are two regions within Chiapas that contain Cenozoic igneous rocks (see Fig. 4 and lower left-hand inset in Fig. 1). The first region lies in central and northwestern Chiapas (within physiographic Provinces 4, 6, and 7). The geologic map of Chiapas classifies the outcrops as early Cenozoic intrusive and late Cenozoic volcanic rocks. Before beginning field work in that area, we spent several days doing aerial reconnaissance. It became apparent from the morphology of the volcanic rocks as seen from low aerial altitudes that the region included domes, necks, and stratovolcanoes of no great antiquity. In fact, we were quite surprised to fly over a volcano, Volcán El Chichón, which had numerous active fumeroles. Volcán El Chichón is also known locally as Volcán de la Unión and Volcán Ostuacán. It is listed as the site of an active solfatara field in the Catalogue of the Active Volcanos of the World (International Volcanological Association, 1951-1973), but apparently it is not well known in Mexico as an active volcano. At a later date we ascended the volcano, which was thickly covered with jungle growth, necessitating the use of machetes to clear a path. The volcano has a central dome, which rises to 1,350 m above sea level, and a surrounding moat at an elevation of 950 m. The flanks are composed of hornblende dacite with a few quartz phenocrysts and disseminated pyrite. Both the moat and the dome are sites of active solfataric activity, which rises some 50 m into the air as extremely hot jets.

Table 1. Plio-Pleistocene K-Ar dates for the Chiapanecan volcanic arc

Sample no.	Material dated, description, and location	K-Ar age and 2 σ error m.y.
1	Whole rock, basaltic-andesite dike, strike N 30° W, dip approx. vertical, Arroyo La Danta, Minas Santa Fe, lat 17°20'24" N, long 93°02'40" W	2.79 ± 0.08
2	Biotite dike in Oligocene shale, strike N 66° W, dip approx. vertical, left bank of Río Ixhuatán between Río Cacate and Río Robajicara, Santa Fe area, lat 17°18'10" N, long 93°02' 18" W	2.29 ± 0.07
3	Biotite, diorite containing pyrite, bornite, and chalcopyrite, intruded into Oligocene limestone which has been converted to wollastonite, 450 m N of La Victoria Mina (Pb-Ag) beside Río Beneficio, near Highway 195, lat 17°22' N, long 93°02' W	2.29 ± 0.10
4	Biotite, unaltered, granodiorite dike in argillic alteration zone, contains disseminated pyrite, La Vuelta de Mico, 1.5 km from Minas Santa Fe on road from Beneficio, lat 17°22'12" N, long 93°02'16" W	2.24 ± 0.08
5	Whole rock, andesite, tilted and underlying pumiceous ash flow, Selva Negra between Rayón and Rincón Chamula on Highway 195 to Pichucalco near km marker 102, Santa Fe area, lat 17°10'18" N, long 92°58'45" W	2.17 ± 0.04
6	Whole rock, augite andesite with disseminated pyrite, Cerro Tzontehuitz, approx. 150 m below microwave tower, lat 16°47'14" N, long 92°36'01" W	2.14 ± 0.04
7	Whole rock, hornblende dacite, from volcanic complex composed of dacitic tuff, lahars, and hornblende andesites, 50 m below microwave tower at 2,800 m elevation, lat 16°47'30" N, long 92°36'01" W	1.95 ± 0.04
8	Hornblende, andesite, from hillside on W side of village of Zinacantán, approx. 2 km N of Pan American Highway, lat 16°44'36" N, long 92°42'36" W	0.850 ± 0.030
9	Hornblende, dacite from Cerro Lanza which is a volcanic rock with vertical flow banding, NNW of Nicolás Ruiz, lat 16°27'16" N, long 92°35'27" W	0.846 ± 0.024
10	Hornblende, dacite on Pan American Highway near village of Navenchuac about 11 km W of San Cristóbal de las Casas, lat 16°43'57" N, long 93°45'12" W	0.432 ± 0.029
12	Whole rock, dacite at 950 m altitude from Volcán de la Unión which was active in winter of 1974 with fumaroles associated with the central dome, near Colonia del Volcán, Santa Fe area, lat 17°24'35" N, long 93°15'10" W	0.209 ± 0.019

The moat is filled with charred logs, and the ground is hot to the touch. The dacite within the moat has suffered argillic alteration and pyritization as well as oxidation to yellow and red ochre. A white sublimate forms around the fumeroles and occasionally native sulfur is present. The dacite yielded a late Pleistocene age (sample 12, Table 1).

Table 1 (see also location map, Fig. 5) includes all of the K-Ar dates we have obtained for this region, which we refer to as the modern Chiapanecan volcanic arc. The oldest dates (2.17 to 2.79 m.y. or latest Pliocene in age (samples 1-5), are for volcanic and intrusive rocks of the Santa Fe mining district-Selva Negra region. Cerro Tzontehuitz, which is an impressive stratovolcano near San Cristóbal de las Casas, is also latest Pliocene in age (approximately 2 m.y., samples 6, 7). Other andesitic and dacitic volcanic fields of that area near the Pan American

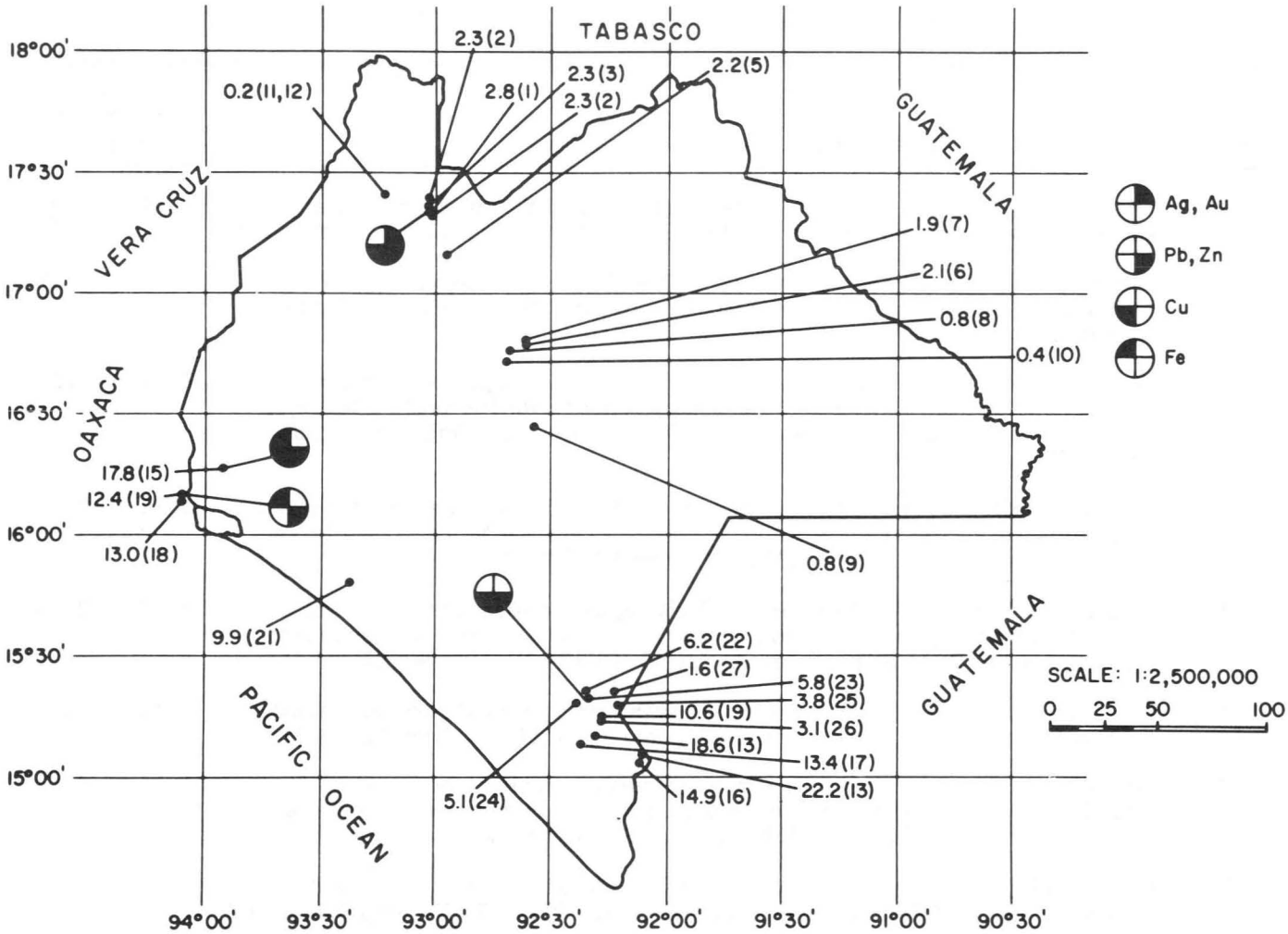

Fig. 5. Location map for samples and mineral deposits given in Tables 1-3 and discussed in text

International Highway in the general vicinity of San Cristóbal de las Casas yielded middle to late Pleistocene K-Ar dates (samples 8, 10). A volcanic plug near Nicolás Ruiz, with conspicuous vertical banding and the appearance of a Pelean spine, also yielded a middle Pleistocene age (sample 9). Thus it is apparent that the modern Chiapanecan volcanic arc is the locus of volcanic activity from at least latest Pliocene time (2.8 m.y. B.P.) to the present.

The second region of Cenozoic igneous activity lies within the Chiapas Massif and the Pacific coastal plain (Figs. 1, 4, 5). We refer to this as the Miocene Sierra Madre volcanic arc. K-Ar dates for this area are given in Table 2. Except for the Motozintla area in the vicinity of the Polochic fault (Fig. 1) where there is a large Pliocene stock cropping out over an area of about 70 km^2, the granodiorite, quartz monzonitic, and granitic stocks within this belt are early to late Miocene in age. The Motozintla stock is latest Miocene or earliest Pliocene in age (approximately 5.5 m.y.).

The geologic map of Chiapas (Fig. 4) includes a large volcanic area in the southeast corner of the state. Actually over much of this area, the volcanic cover has been removed exposing a granitic batholithic complex of Miocene age (10.6 to 22.2 m.y., samples 13, 14, 16, 17, 20). Volcanic rocks other than from the modern, majestic stratovolcano, Tacaná, do crop out in the area. For example, Cerro Boquerón, which is the remnant of an andesitic volcano, dates 3.13 m.y. (sample 26). The unwelded Pleistocene tuff near Motozintla contained fresh hornblende which yielded an early Pleistocene date (1.62 m.y., sample 27). The outcrop is weathered, which made identification of its mode of transport difficult, but it has aspects of an ash flow. Its source is not known, but most probably it originated to the east toward Guatemala.

The distribution of volcanic and subvolcanic rocks in Chiapas suggests that there has been a radical change in the geometry of the subducting Cocos plate between the time of emplacement of the plutons and volcanic rocks of the Miocene Sierra Madre arc in Chiapas and the emplacement of the stratovolcanos and related plutons in the modern Chiapanecan volcanic arc (Fig. 1, insert). This reorganization appears to have occurred between the time of the emplacement of the Miocene stocks and the extrusion of volcanics in the Santa Fe mining district, that is, between about 9 and 3 m.y. ago. The Pleistocene volcanism in southeastern Chiapas seems to be associated with the Central American arc on the Caribbean plate side of the Cuilco-Chixoy-Polochic fault rather than with the American plate.

It is interesting that the earthquake hypocenters associated with the subducting Cocos plate are anomalously shallow from about Mexico City southeast to the Isthmus of Tehuantepec, distances being measured perpendicular to the Central American trench (Molnar and Sykes, 1969). Southeast of the Isthmus of Tehuantepec, the hypocenters rapidly deepen moving inland from the trench. The volcanic axis follows a similar pattern moving inland southeast to the Isthmus of Tehuantepec and then moving closer to the Pacific Ocean southeast of the Isthmus of Tehuantepec. Within the Caribbean plate, the Central American volcanic arc fairly closely parallels the Pacific Coast and the Central American trench. The modern Chiapanecan volcanic arc represents the volcanic arc returning to the coastal region. There is no gap in volcanism between the modern Chiapanecan volcanic arc and the Mexican volcanic arc; the apparent gap in Figure 1 is filled by a large volcanic center around San Andrés Tuxtla and an almost continuous volcanic outcrop to central Veracruz. There is, however, a real gap in Chiapas between the Chiapanecan and Central American arcs. We have searched for but have not found volcanic rocks within the Central Depression of Chiapas (Province 2, Fig. 3). The apparent gap to the northwest is an artifact of the manner of constructing Figure 1 in which the arc is made to pass through the center of volcanic outcrops.

The convex-to-the-north pattern of the Mexican-Chiapanecan volcanic arcs is probably the result of a bending of the subducting Cocos plate which steepens to the northwest and southeast and is very shallow in between the two segments of what is almost a continuous volcanic arc. Prior to about 9 m.y. ago the Central American arc continued to parallel the Pacific Coast and Central (Middle) American trench northwestward through Chiapas to Oaxaca and, quite probably, although evidence remains to be documented, through Guerrero, Michoacán, and Jalisco. The previous arc was active for at least 13 m.y., prior to the Pliocene epoch. It is interesting that this reorganization appears to be approximately correlative with events to the north. According to Larson (1972, p. 3345): "The Middle American Trench north of the Rivera Fracture Zone became nearly dormant as a plate boundary 8 to 10 m.y. ago when the rise crest changed from the Pacific-Farallon to the Pacific-Rivera plate boundary."

Relationship Between Volcanism and Metallogenesis in Chiapas

There are a number of significant mineral deposits within the Miocene Sierra Madre arc. The region of the Motozintla stock has been set aside by the Mexican Government as a mineral reserve. We examined a porphyritic outcrop at Tolimán (site of sample 23, Fig. 5) with disseminated sulfides and veins which appears to have all the aspects of a classic disseminated porphyry copper deposit. Within a mile of this outcrop, argillic and propylitic as well as potassic alteration can be observed. Under the hand lens, pyrite, bornite, chalcopyrite, and sphalerite were abundant and readily observable.

Cerro Colorado (sample 15 location, Fig. 5), which is only 100 m from the coastal railroad, also has the typical characteristics of a porphyry copper-limestone contact zone. The prospect occurs within a hill, which is capped by marble, silicified limestone, and magnetite. Malachite, azurite, sphalerite, galena, and asbestos were observed. What appeared in the field to be sericite was found in the laboratory to be almost pure paragonite, suggesting alteration by a hydrothermal convection system involving sea water.

We also collected from the La Carmen prospect in Oaxaca near the Chiapas border (sample locations 18, 19, Fig. 5). La Carmen is a contact metamorphic deposit of granodiorite in limestone. The most important mineral is magnetite. However, zinc blende (sphalerite) is very abundant. The limestone is converted to marble and wollastonite. We collected a sample of zinc ore with greenish books of mica about 1 cm in diameter. Much to our surprise, this mica also was shown to be paragonite in the laboratory, again suggesting that the coastal area was inundated by sea water in mid-Miocene time.

Much of the Chiapas Massif is most probably an excellent target for Miocene ore deposits associated with the roots of stratovol-

canos. Most of the Chiapas Massif is quite inaccessible, and time did not permit a thorough reconnaissance. However, we examined stream gravels between the sampled outcrop (sample location 21, Fig. 5) and long 92°40' W. Volcanic and subvolcanic rocks are abundant in the cobbles in the rivers between those coordinates along the coastal highway.

There is one mining area within the modern Chiapanecan volcanic arc around Santa Fe (sample localities 1-4, Fig. 5). At Santa Fe there are large underground workings which were mined for gold by an English company just before the Revolution of 1910. A French firm mined gold in the area following the revolution. At the present time, Minera Corza has a lease on the property. There is abundant copper, zinc, silver, and lead mineralization as well as gold. Sulfide minerals are ubiquitous within a stock outcrop of 2,000-m radius. Mining continued at the La Victoria mine until 1972. The Santa Fe mine proper is a contact metamorphic deposit with granodiorite intruded into Oligocene limestones forming a pure-white wollastonite cap. Vein deposits have also been mined. Disseminated sulfides occur throughout most of the stock that we examined.

Unlike many Mexican states, there is little tradition of mining in Chiapas. Nevertheless, both the modern and Miocene arcs provide a fruitful field for exploration. The presence of stratovolcanos in all stages of dissection by erosion and the association of sulfide mineralization with the remnants is in conformity with the relationships suggested by Sillitoe (1973) between stratovolcanos and porphyry copper deposits as well as lead, zinc, and previous metal veins and replacements.

The rate of erosion required to erode stratovolcanos in the Motozintla area is not unreasonable. The majestic stratovolcano Tacaná rises from the Pacific coastal plain to an altitude of about 4,050 m. According to Sillitoe (1973), the tops of porphyry copper deposits begin at a depth of 1.5 to 3 km. The deposit at Tolimán (Motozintla stock) appears to be eroded below the top as defined by Sillitoe, but erosion would have to continue to a much greater depth, according to his model, to expose the bottom of the deposit at Tolimán. A reasonable estimate would be erosion to a depth of 4 $\pm$ 1 km in 6 m.y. or about 660 $\pm$ 170 m/m.y. At this rate, only 12 m.y. would be required to erode 8 km and reach the bottom of a porphyry copper system in the Motozintla area. In fact, we have dated a number of unmineralized granites in southeastern Chiapas at from 11 to 22 m.y. (samples 13, 14, 16, 17, 20 in Table 2), which is in good agreement with the time required to reach the bottom of porphyry copper systems. The amount of erosion in 3 m.y. would be about 2 km or insufficient to completely remove the volcanic apron around volcanos of that age. The preservation of andesites at Cerro Boquerón of 3 m.y. age is quite compatible with the postulated rate of erosion.

In the Santa Fe mining district and at Cerro Tzontehuitz, 2 m.y. has not been sufficient time to remove the volcanic apron. Erosion rates in the Arriaga area, which has a lower rainfall, must be less than 660 m/m.y. or the mineral deposits at Cerro Colorado and Mina La Carmen would have been destroyed by erosion. However, the erosion rate in the Arriaga district need not be less than 300 m/m.y.

It is unlikely, with this rate of erosion, that pre-Neogene porphyry-type deposits would be preserved within the Chiapas Massif. Consequently, the Permian batholith and old igneous rocks would not be expected to be likely prospects for porphyry-type deposits. However, the entire length of the Sierra Madre del Sur from Cape Corrientes to Guatemala is a likely target for Neogene porphyry-type deposits.

Conclusions

Two Neogene volcanic arcs can be defined within Chiapas. The Miocene Sierra Madre volcanic arc was abandoned between 9 and 3 m.y. ago when the modern Chiapanecan volcanic arc came into existence as a result of a reorganization of the subducting Cocos plate. Both Neogene volcanic arcs are the locus of mineral deposits associated with calc-alkalic stratovolcanos in accord with Sillitoe's (1973) model. The rate of erosion required to expose these mineral deposits is between 300 m/m.y. and 900 m/m.y.

The still-active modern Chiapanecan volcanic arc is essentially continuous with the Mexican volcanic arc (Mexican volcanic axis or Eje Volcánica). The ancestral Miocene volcanic arc was probably continuous with the Central American volcanic arc from the eastern extremity of the Panama fracture zone to Cape Corrientes.

Both the ancestral volcanic arc, which parallels the Pacific Coast and the Central American trench, and the modern Chiapanecan arc, which is convex to the north, are prime targets for Neogene ore deposits.

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This work would not have been possible without the constant support and encourage-

Table 2. Neogene dates for the Sierra Madre del Sur and coastal plain in Chiapas and neighboring Oaxaca

Sample no.	Material dated, description, and location	K-Ar age and 1 σ error m.y.
13	Biotite, biotite-hornblende granite, collected beside the Puente Monte Perla at 1 km on road from Tuxtla Chica to Unión Juárez, lat 15°03'04" N, long 92°05'47" W, Chiapas	22.2 ± 0.5
14	Biotite, granitic intrusion, 1 km S of Finca Santa Anita, Motozintla area, lat 15°08'46" N, long 92°20'25" W, Chiapas	18.7 ± 0.4
15	Whole rock, altered quartz monzonite with paragonite, epidote, and tourmaline, intruded into a cap of marbleized limestone; chalcopyrite, malachite, azurite, magnetite, and sphalerite within the contact zone; at Cerro Colorado, 100 m from coastal railroad, 5 km NW of Arriaga, lat 16°16'57" N, long 93°58'20" W, Chiapas	$\leq$ 17.8 ± 2.6 (may contain significant amount of excess radiogenic argon)
16	Biotite, granitic intrusion on the flank of Volcán Tacaná, about 200 m E toward Juárez from the Finca Muxval, Unión Juárez area, lat 15°04'47" N, long 92°04'33" W, Chiapas	14.9 ± 0.3
17	Biotite, granitic intrusion with pyrite, Finca Chajul in Cerro Soconuscos, Motozintla area, lat 15°10'51" N, long 92°18'08" W, Chiapas	13.4 ± 0.3
18	Biotite, granodiorite, Arroyo de Mangos, SE of La Carmen mine, approx. 1 km from Pan American Highway, Tepanatepec area, lat 16°26'24" N, long 94°06'33" W, Oaxaca	13.0 ± 0.3
19	Biotite, granitic intrusion into Cretaceous limestone with zinc blende (sphalerite) and wollastonite in contact zone, samples in Arroyo between Cerro La Carmen and mineralized hill, about 500 m SW of Pan American Highway, Tepanatepec area, lat 16°26'31" N, long 94°06'32" W, Oaxaca	12.4 ± 0.3
20	Biotite, hornblende-biotite granite, on road from Cerro Boquerón to Berriozábel from Motozintla about 4 km from Niquivil junction, near Tzuma, Motozintla area, lat 15°16'38" N, long 92°17'01" W, Chiapas	10.6 ± 0.2
21	Biotite, granite outcrop along coastal highway at the Potrero de la Gringa, Finca Perseverencia, Tonolá area, lat 15°50'17' N, long 93°28'02" W, Chiapas	9.95 ± 0.27
22	Sericite, pyritized fanglomerate, Mina de Concepción, Motozintla area, lat 15°20'34" N, long 92°20'47" W, Chiapas	6.18 ± 0.13
23	Biotite, K-silicate altered quartz monzonite porphyry with pyrite, bornite, chalcopyrite, and sphalerite, below the bridge at Tolimán, Motozintla area, lat 15°19'08" N, long 92°19'50" W, Chiapas	5.75 ± 0.10
24	Biotite, granodiorite porphyry intruded into the metamorphic complex of the Rancho Campeche area, km 27.5 on road from Belizario Domínguez to Motozintla S of Rancho Campeche, lat 15°18'34" N, long 92°22'27" W, Chiapas	5.08 ± 0.11
25	Whole rock, dacite, collected about 15 m from Chiapas-Guatemala boundary marker, Niquivil, lat 15°15'46" N, long 92°12'38" W, Chiapas	3.78 ± 0.16
26	Whole rock, andesite from summit of footpath from Berriozábel to Finca Hamburgo on the S side of Cerro Boquerón, Motozintla area, lat 15°15'10" N, long 92°16'34" W, Chiapas.	3.13 ± 0.07
27	Hornblende, unwelded tuff, 500 m S of Motozintla on highway to Buenos Aires, lat 15°20'46" N, long 92°15'40" W, Chiapas	1.62 ± 0.16

Table 3. Data for K-Ar ages in Tables 1 and 2

Sample No. (laboratory no.)	% K	Argon: Radiogenic x 10^{-12} moles/g	Argon: Atmospheric %	Age ± 1 σ m.y.
1 (UAKA-74-25)	1.99	9.55 9.70	57.4 56.9	2.79 ± 0.08
2 (UAKA-74-23)	7.18	28.39 28.70	60.8 60.5	2.29 ± 0.07
3 (UAKA-74-22)	7.48	30.09 29.39	74.0 74.9	2.29 ± 0.10
4 (UAKA-74-24)	7.67	30.44 29.18	66.1 67.4	2.24 ± 0.08
5 (UAKA-74-21)	2.87	10.87 10.75	17.8 17.7	2.17 ± 0.04
6 (UAKA-74-32)	2.22	8.36 8.15	10.8 11.0	2.14 ± 0.04
7 (UAKA-74-31)	2.63	8.88 8.90	24.5 23.8	1.95 ± 0.04
8 (UAKA-74-33)	0.79_8	1.20 1.16	85.9 86.0	0.850 ± 0.030
9 (UAKA-74-30)	1.05	1.58 1.50	80.3 81.1	0.846 ± 0.024
10 (UAKA-74-34)	0.95_5	0.74 0.69	82.3 83.2	0.432 ± 0.029
11 Hbld. (UAKA-74-26)	1.20	0.24 0.26	96.3 96.0	0.120 ± 0.038
12 WR (UAKA-74-26)	2.28	0.85 0.80	87.1 87.9	0.209 ± 0.019
13 (UAKA-75-35)	7.28_4	281.4 281.6	16.0 16.6	22.2 ± 0.5
14 (UAKA-75-37)	7.73	251.0 251.8	27.9 27.7	18.7 ± 0.4
15 (UAKA-74-101)	0.024_2	0.73 0.77	92.9 92.4	17.8 ± 2.6
16 (UAKA-75-31)	7.58	193.8 199.2	35.7 33.4	14.9 ± 0.3
17 (UAKA-75-36)	7.63_4	178.0 179.0	12.8 12.4	13.4 ± 0.3
18 (UAKA-74-103)	7.42	169.3 167.4	17.4 18.3	13.0 ± 0.3
19 (UAKA-74-105)	7.11	151.3 154.0	51.4 51.1	12.4 ± 0.3
20 (UAKA-75-39)	7.41_2	134.4 138.5	38.5 37.6	10.6 ± 0.2
21 (UAKA-75-34)	7.62	123.5 125.3 126.2 128.1	54.0 41.8 54.2 43.4	9.95 ± 0.27
22 (UAKA-74-113)	7.72	83.2 82.7	26.4 26.4	6.18 ± 0.13
23 (UAKA-74-112)	7.28	72.2 73.2	30.1 29.7	5.75 ± 0.10
24 (UAKA-74-114)	6.96	61.7 61.2	37.9 39.5	5.08 ± 0.11
25 (UAKA-75-38)	2.50	16.13 16.69	73.8 73.3	3.78 ± 0.16
26 (UAKA-75-32)	1.92_4	10.44 10.45	22.9 21.5	3.13 ± 0.07
27 (UAKA-74-108)	0.45_6	1.36 1.21	86.8 88.2	1.62 ± 0.16

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THIRTY-YEAR EVOLUTION OF PORPHYRY COPPER EXPLORATION IN SOUTHWEST USA[1]

PART 1. TECHNIQUES AND PHILOSOPHIES

by

Kenyon Richard[2]

More or less 30 years ago there was a gradual but profound change in mineral exploration —particularly in porphyry copper exploration.

Functioning for the first time in organized, systematized groups outside of their home districts, mining geologists themselves became regional prospectors.

In order to explain that last statement, I feel that I must go back, not just 30 years, but into the last century, even earlier, for a number of comparisons, because the contrast in exploration procedures is distinct; and by no means are the distinctions all due to new technological capabilities.

Through very early Biblical times, and the Cypriots, Romans, and Conquistadores, to name a few, the prospector-miners were slaves. That's low-cost operation at its lowest, particularly because the families of the slaves had to feed them.

The Queen of Sheba is a good example of ingenuity. She operated a lode gold mine. The slaves who rotated her hand ore grinders were blinded. Even if they did find nuggets, they couldn't escape. She certainly needed no time-motion analyst to explain the meaning of operational efficiency. Her biggest headache probably was maintaining a monopoly on the slave market because her labor turn-over must have been high due to early insanity among the workers.

The first "free" prospectors in history were the California '49ers. They were free, that is, to blister in summer, freeze in winter and starve year-round. On average they barely made wages. But they came from all over the world and they didn't return home when the placer gold deposits were soon worked out. Some became ranchers, store owners, blacksmiths, and the like, and most prospered; but some took their California gold pans, spread out over the West, learned to detect other heavy minerals and metals, and taught themselves and their successors a few characteristics of ore deposits. These men became the prospectors, and a very few of them became the discoverers of bonanzas, the real founders of the burgeoning mining business of the West.

However, most of them ruined themselves with hard, useless work because they lacked education—even the rudiments of business, engineering, or geology—partly because it was not available, but mostly because they were too rough-hewn to have bothered with it anyway. Consequently, they tended to regard almost any mineral showing as a probable orebody; they simply did not recognize the tremendous odds against success; they were imbued with the Western tradition of toughness; and they were sustained by that marvelous incentive for human endeavor: the dream of instant wealth. Altogether, the thousands of miles of hand-driven workings on worthless mineral showings is staggering to contemplate.

They found many thousands of mineral deposits. But with the exception of those few bonanzas, the instant wealth didn't materialize.

Most of the prospectors realized rather early they could not convert the discoveries of seemingly fairly good mineral showings into instant wealth either by themselves or in hard-working small groups. To some of the discoverers it became evident that the making of mines required talents and resources they lacked: First, an understanding of geology such that a discovery could be evaluated without blindly undertaking a terrible amount of fruitless hard work; second, an appreciation of mining engineering, management, marketing, etc; and most important, a supply of money and knowledge of its use.

The bonanza discoveries, of course, early attracted money along with engineering and management talent. When the ore was rich, however, the mine operators could and did make many expensive exploration blunders—unnoticed. So, recognition by anyone of a need for knowledge of the geology of mineral deposits evolved very slowly.

The earliest individuals doing "mining"

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geological work of a special kind—for example, men like Becker and Hague of the Survey who published classics respectively on the Eureka and Comstock Lode districts of Nevada in 1882 and '83—were only scientific observers and describers, educated in Europe—and they worked only on the known bonanza deposits.

The same can be said for the next generation of geniuses, such as Ransome and Lindgren. They were marvelous scientific observers; they were not discoverers; but they were teachers, inasmuch as their publications and their fame improved and speeded the movement of the knowledge of mineral ore occurrences from European universities to eastern United States and on to the West.

Rather tardily, mining geology became available in the West. The more progressive mining companies began to hire men with education in the science of mineralization. Their exploration judgment gradually began to replace the whims of the mine shifters, the superintendents, the surveyors, the astrologers, and the like.

Anaconda formed the first and justly famous geological department. Other companies, large and medium sized, imitated Anaconda because of its reputed great success in ore finding. These new departments in other companies also found ore. The very important point here is that these departments of mining geology and their increasing knowledge of ore occurrence primarily functioned to find ore in company-owned mines, properties and districts. With the exception of checking out some prospects brought to their attention, no mining geologists really were prospecting for new districts in a regional sense—at least, they were not getting far from home base.

The rapidly improving knowledge about mineralization was still not directly available to to the prospectors. As time went on they still did not understand, themselves, really how to evaluate a newly discovered mineral showing, or for that matter, how to check out an old prospect in light of new economic conditions.

So—a technique evolved which had innumerable variations and ramifications and which I can only crudely describe here.

I term it the "walking through the door" technique. After digging around a bit on a new discovery—or possibly opening up the workings of an old prospect acquired with his second cousin's life savings—the prospector collected a few samples and specimens and went in search of the right office door to walk through. This might be the office of a nearby small mine manager, or the friend of a friend who knew a fellow who . . . , etc., or a lawyer, or a promoter who knew a mining vice president. Briefly, he had to get through a door behind which was the right combination of money and exploration-mining talent. This usually meant a medium-to-large company.

If he walked through that right door, it only meant that his mineral showing would get a proper evaluation, hopefully favorable and with a follow-up. If not, there were other mining company doors. Otherwise, there were doors such as stockbrokers'. In those days money from stock sales seldom involved much in the way of preliminary evaluation of a prospect; blatant misrepresentation was common; but money from valid stock sales did find and develop many orebodies.

The implication is not intended that the men with exploration and mining talent and the money managers were hiding behind their doors doing nothing but wait for bonanzas to walk in. They were quite busy with their own mines. Rather, and this is the whole point, the prospectors and promoters were keeping the mining companies sufficiently supplied with "outside" prospects worth the gambles of exploration and development. As a result the supply of base metals was being augmented enough to keep up with the demands of the growing industrial revolution. The mining geologists not only lacked the time, it wasn't even necessary for them to become real regional prospectors outside of their home mines and districts.

This system worked even though it grew accidentally; it was unorganized and haphazard, and it was unfair to the prospectors. It worked because the successive generations of prospectors had those recurring visions of the rainbow's end. Even if the rudiments of knowledge about mineral occurrences—and their vagaries—had been available to the prospectors of, say, 70 and 100 years ago, they wouldn't have listened because, if I may repeat myself for emphasis, all of those men were motivated by the delusive incentive of instant wealth.

The walking-through-the-door system was still functioning—willy-nilly, but effectively—when I got out of college. And in one form or another it will always be part of the business.

The first organized exploration program in history was undertaken, I believe, when World War II was looming and the U.S. military was shocked (and probably indignant) to learn that God had not provided instant domestic orebodies of quite all the minerals and metals the generals wanted for a new war. No brilliant exploration ideas seem to be immediately at hand, so the government reacted by

legislating instructions to the U.S. Bureau of Mines to find orebodies of seven strategic metals and minerals. For at least two reasons this was a dirty trick on the Bureau: First, they didn't really have good reasons to know where and how to explore for new supplies of these strategic items; and second, being very conscientious mining engineers, they thought they were supposed to know.

The Survey was fitted into some advisory capacity to the side and provided considerable help, so I understand, particularly when another law enhanced the problems by adding six more short-supply items.

A massive bureaucratic effort was made in which there was a great rejuvenation of interest in prospects and properties, practically all of which had already been turned down as too risky by private companies, usually by several, but, mind you, always on the basis of non-wartime economics . . . A new "through the door" procedure developed. It became a mad dash, not a walk, because the exploration money was not only free, it was wrapped in patriotism. Despite this frenetic atmosphere, the basics of the old system still prevailed. The prospector, or mineral property owner, or small-mine owner still had to get the attention of the experts behind the door. This time the door was government. The experts were more concerned with the collection and accuracy of details, but somewhat less concerned with exploration risks.

Despite the Bureau's mandate, which could have invited some pretty wild exploration, prospects and properties were checked thoroughly. Many drilling risks were taken, but only with care and thought. A few tons of ore were found here and there, but only one real discovery—San Manuel—resulted from the entire program, and that was too late to benefit the war effort. B. S. Butler of the University of Arizona and earlier USGS fame, and Nels Peterson, USGS, were the instigators of that discovery.

Considering their sincere efforts, the men conducting that major wartime exploration project deserved more luck. If viewed strictly from a commercial standpoint the program failed. The profit from ore found was small as compared with the program's cost. But, of course, it was not really supposed to be a commercial success. From philosophic and scientific aspects, however, I believe it was successful. It had only a few new geologic concepts for original impetous, but the published results eventually were of great value to future workers.

The big changes in exploration, particularly porphyry copper exploration in the Southwest, took place after World War II. The results of the Bureau and Survey programs had an effect; but the changes were not directly related to the war's end or to dramatic economic changes, or, since Ralph Nader hadn't arrived yet, to any great public outcry that something had to be done about something.

Rather, the realization gradually evolved in the minds of a few that, at least in the case of porphyry copper, it was possible that neither the prospectors nor the earlier geologists had really known how to find any but the rather obvious ore districts. The San Manuel discovery probably had some effect on this line of thought. This meant that (1) some other porphyry copper orebodies could be around somewhere and (2) the mining geologists had to re-do the copper prospecting job themselves.

There were other factors related to the changing copper exploration philosophy, and I'll get to those momentarily. First, though, let me indulge in a bit of narrative because I was involved somewhat myself. If you haven't already, you will note some difficulty in my being objective about a philosophy which is mostly subjective anyway.

E. N. Pennebaker, as consulting geologist for Consolidated Coppermines Corp., originated and conducted the first systematic program of regional prospecting for porphyry copper orebodies in the Southwest. It was begun in '48 and continued until '52 when the company was beginning to fold.

Penny had a staff of four to six young but excellent geologists. Ray Ludden, now manager of western exploration for Phelps Dodge, was one of the group. Their specific objective was to find new porphyry copper alteration zones. They used the state map to spot Laramide intrusives and they combed the Mines Handbook for leads like FeO-cemented gravels and for fringe manganese deposits like Bisbee and Ely. They jeeped and walked all over the place. They found about a dozen porphyry copper deposits not known as such theretofore, although a couple were near known porphyry districts. After finding an alteration zone, they would map in detail with particular attention to leached capping interpretation.

They drilled several holes in each of four, which I'll identify as Safford, Kelvin, Patagonia, and Yerington. I believe they penetrated ore-grade material in all four and they had one drill hole in the middle of what is now Kennecott's big Safford orebody. That's a pretty good record considering that they were constrained with the need for a +1.0% Cu orebody at a 0.6% cutoff. The copper price

didn't jump quite soon enough for them, that's all. They were mining geologists who became the first organized group that didn't wait for a porphyry copper prospect to walk through the office door.

While working at Silver Bell and then in southern Peru in the late '40s on some of those copper deposits, particularly Toquepala, Harold Courtright and I began to realize that green copper-stained outcrops could be seriously misleading in terms of copper sulfide ore occurrence. (By cutting myself in on this, I'm stretching things a bit because, as I suppose some of you know, I'm color blind—green copper stain comes through as a nice clean gray—so, I wasn't mapping the stuff anyway.) I did, however, contribute in various ways. I can assure you there was no great flash of insight involved. In fact, there were many complicated aspects of Toquepala geology: We were busy disagreeing about a lot of these other things, and I don't believe we began to think much about the copper-stain business until later when I had had a chance conversation with Juan Oviedo, the original owner of Toquepala. It then became evident that Cerro de Pasco had almost walked away from Toquepala without testing the sulfide zone. Apparently they thought the copper-stained outcrops were the guide to ore. What I want to emphasize is that, if Cerro had walked away, Southern Peru might today still be a rugged, discouraging desert with 2 or 3 billion tons of untested copper ore.

A steep-walled canyon cut the middle of the Toquepala deposit. A few small patches of weak copper-staining occurred high on the canyon walls in the fringe zones of alteration. Cerro had driven about eight adits, 250 m each, beneath these surface copper showings. They cut no sulfides and their adit assays were sometimes as high as 0.1% Cu. They were prepared to move out their camp. So, in desperation rather than with knowledge, Oviedo sank a shaft in the bottom of the canyon. Within 15 m his shaft encountered disseminated chalcocite averaging 4.0% Cu. Cerro stopped packing and started drilling.

Actually, Harold and I were rather slow to catch on. But we began to discuss the possibility that porphyry copper sulfide ore easily could occur in many other places without the need for directly overlying copper-stained outcrops.

The idea was simple, but a lot of other geologists had not caught on either. I worked with Blanchard for several weeks in '47 and I've talked with Locke and Tunell. I believe they all thought of the technique of leached outcrop interpretation, which they originated, as being useful in finding more ore in already discovered districts. It seems rather incredible, but I don't believe they considered it as being a means of discovering entirely new, separate deposits or districts by re-prospecting large regions. None of their publications state this as a possibility.

Anyway, Courtright and I thought the idea was important enough to warrant re-prospecting the Southwest United States and many other regions.

American Smelting didn't exactly respond with alacrity to my report describing how this prospecting should be done. While working on the Flux mine in the Patagonia Mountains, however, Courtright recognized porphyry copper alteration without copper stain, and I was sent to check it out early in '51.

That's where we ran headlong into our old friend Pennebaker and his crew. We had worked for Penny in the 30s and 40s at Ely, and we knew Ray Ludden and others of his crew. Also, Phil Jenney, representing Coppermines' partner, American Metals, used to show up frequently. We all stayed at the same motel and, as you can imagine, altogether there was quite a bit of socializing while we were stealing secrets from each other.

Of course, it was immediately evident that, although arrived at independently, our basic exploration ideas and Pennebaker's were about the same, only he was three years ahead of us.

Anyway, between Patagonia and the border there were plenty of porphyry copper alteration zones and breccia pipes for everyone. A number of holes were drilled, but there was no significant chalcocite enrichment. We all pulled out. Too bad none of us had the instincts of real estate operators. In terms of one kind of exploration philosophy and how it changed, everyone then was using about 18¢ copper when making projections into the dim, distant future of, say 1960 or '65.

I've dealt with the leached-capping-without-copper-stain idea rather at length because, although a simple geological idea, it had been overlooked. It got some drilling programs started. In turn, that activity got other groups interested. And so on.

Also, though, at about that time important new geophysical, geochemical, and other techniques were appearing and adding significantly to the changes in exploration. A change more important than the advent of new techniques, however, was taking place.

The evolution of exploration philosophies

has been primarily a matter of changes in the methods of managing exploration. For a very long time the average mining community was isolated, and even the large operations all began in isolation. In those circumstances the local mining engineer-mine manager was king. He had to know how to do almost anything and he did. All problems arrived in front of him immediately, and his solutions were fast and usually good.

As the isolation problem became uncommon and as the whole mining business became large, complex and, for the individual, specialized, the concept that the mine engineer-operator still should be the real decision maker prevailed for a remarkably long time.

At this point I'll bring up Kennecott—not because I know more about that company than the rumor mill normally provides—but because for such a long time they completely ignored exploration. It wasn't a technique, a philophy or a problem. Once in awhile a manager would point to an area on a map, some holes would be drilled, 10,648,321.4 tons of ore would be added to reserves and—so what is unusual?

In the late 30s the manager of one of their operations, and a nice guy nonetheless, gave me some friendly advice. I was working for a neighboring company; he knew me only slightly; but he could tell I was taking my job too seriously. He said "A geologist might be all right, but I prefer a churn drill."

In those days Kennecott could afford managers like that, but the breed flourished in many companies where it was ill-afforded.

As I remember it, sometime in the late 40s a well-known geologist named Anthony Gray (African experience mostly, I think) persuaded the Kennecott board to undertake a massive exploration program. That in itself was a full 180-degree turn, but the hard-to-believe part was the corporate managerial arrangement.

Bear Creek was set up as an exploration entity having no connection with the system of operating mine management.

Gray had retired, and I have no knowledge of his effect on policy beyond my understanding that he accomplished the establishment of Bear Creek. Jim Boyd, a mining administrator of established talent, but a far cry from the old-time mine operator boss, ran the show; and the size of his money supply was hard to believe.

I have never learned of any especial geological idea or combination of exploration techniques that motivated the formation of Bear Creek. So, my own thought is that Kennecott decided first to collect a big bunch of talented geologists, and the exploration ideas then were bound to evolve. They did.

Bear Creek people soon were all over the place. In many ways they influenced nearly all facets of porphyry copper exploration. For example, besides many geophysicists, geochemists, and photogeologists, they had field geologists specializing in regional reconnaissance, and others in detailed mapping, and scientists combining specialized field and sophisticated laboratory studies; they had mining engineers, mineralogists, geological researchers, statisticians, economists, computer programmers, drilling specialists, and so on.

I'm not necessarily expressing approval of all of the Bear Creek setup and procedures; but I do emphasize that their influence on the administration and methods adopted by other exploration organizations was pronounced.

Many exploration groups moved into the Southwest in the 50s and 60s. Some just intended to determine, briefly, what was going on. Most stayed to do a lot of reconnaissance work; and, because an array of technical improvements and new developments were just coming out in geophysics, geochemistry, and photogeology, they continued with projects. The detailed list is long under each of these headings of techniques; so a new group could quickly become involved in various combinations of these techniques—and many did just that.

Most groups concluded, too, that because they were covering new ground they should properly do their own geological mapping to back up whatever geophysical or other survey they might be conducting.

Thus, field work of many types was conducted over large tracts.

Despite the title of my talk I've no intention of commenting upon or even listing all of the activities and variations that could be considered as new or specialized exploration techniques used around here. There isn't time really to deal with the popular ones, let alone all of those which, in my opinion, either did not apply, or were overused. But I must mention a few factors that spurred and maintained exploration in the Southwest.

First, the real price of copper stayed ahead of all predictions, even if we average in a couple of episodes like the past year and a half.

Second, both the quality and quantity of publications on ore deposits and related geology in general and porphyry copper-molybdenum in particular increased remarkably in the past 20 years. Certain universities (the University of Arizona up with the top) and the USGS contributed most; some trade journals came out with surprisingly useful papers, and even private industry cut loose with some remarkable material on rare occasions.

Third, as the mining geologists became prospectors they learned that, despite the great amount of geological work of all kinds in the Southwest over the past 100 years, and particularly the last 30, there are still more uncertainties and complexities, though of different kinds, than 30 years ago. What appeals to me is that so many of these "new complexities" have relationships to exploration possibilities.

Of course, the high percentage of postmineral cover rocks in the Basin and Range province is always attractive to explorationists for many reasons.

Fourth, my friend who will be talking about case histories here tonight is certain not to deal properly with an episode which I believe had a most important effect on the exploration business.

Discovery always involves many people. Dave Lowell's Kalamazoo affair, however, was as close to being a one-man show as anything I know of. He demonstrated that the best of geological work may be subject to new or improved interpretations. This, however, requires logical thought, thoroughness, and time. Nowadays we have to hurry most of the time. I believe Dave showed us, however, that one of the keys to discovery is to know when to slow down and be thoughtful and thorough.

I'm constrained to add a precaution which you may find surprising. Certain lines of geological thought attain prominence as having possible value to exploration for one reason or another. Really, though, they are intellectual games, mostly. Please understand, I enjoy playing some of these games myself, but when exploration is involved a sharp distinction should be drawn between practical and impractical.

A couple of examples:

1. I am personally convinced that "lineaments," alignments, structural zones, or whatever the name, were important localizers of <u>some</u> porphyry copper deposits. But these structural conditions are very obscure in most cases and should be postulated only with care. A few years ago lines were being drawn all over the Southwest—the matter had become an intellectual game, and, as such, its real exploration value became obscured—almost valueless.

2. Plate tectonics is a wonderful subject of new scientific thought. But a tremendous amount of world-wide field work must be redone to improve its authenticity. Pictures of hydrothermal systems appear on sections of subduction zones. That alone is all right. But if there is a statement or an implication that up-to-date knowledge of plate tectonics will give me the longitude and latitude of a brand-new porphyry copper deposit in a year or two, I know we are playing intellectual games again.

All of us must use care in distinguishing the intellectual games from the practical aspects of geologic thought and conversation.

As an example of practicality, I would like to present my concept that the first real prospecting event occurred during pre-history. In case some of you are not up to date, pre-history is that gray area in time between recorded history and what I usually term "PB," or Post-Baboon. That terminology is easily confused with the newly accepted scientific initials "BP," or Before Present. I understand there is a group which maintains there <u>is</u> no time gap between Before Present and Post-Baboon.

Anyway—upon being pushed out of a tree an angry post-baboon—pre-person hurriedly picked up a chunk of yellow rock and threw it at her husband. It was heavy and knocked him cold. This so fascinated the pre-person (post-baboon, that is) that she took the summer off and went prospecting for another, bigger chunk of gold so she could really finish him off. I believe she was committed because a tribe of environmentalists discovered her prospecting license had expired.

PART 2. CASE HISTORIES OF DISCOVERIES [1]

by

J. David Lowell [2]

The period following World War II has seen a wave of porphyry copper discoveries in the Southwest with the bulk of these deposits having been found in southern Arizona. The attached tabulation of several selected features of each discovery has been prepared in an attempt to point up changes in techniques over this 33-year period, together with changes in the typical settings of deposits found.

A discussion of discoveries is always a subjective matter from the standpoint of who was responsible and which technique was responsible for the discovery. There are invariably rival claimants, however, the discovery typically results from a team effort of several different geologists, supported at different levels of management, sometimes aided by geophysists and geochemists, and often basing their work on regional geologic mapping, or stratigraphic or tectonic relationships worked out by geologists in government agencies. Peter Joralemon has pointed out in a recent paper that the contribution of prospectors or engineers or metallurgists is also the significant factor in many discoveries.

During the 33-year period covered by the tabulation (Table 1) fundamental changes have occurred in the parameters for porphyry copper exploration in the Southwest which are reflected to some extent in the tabulation. The most obvious change is the fact that, for practical purposes, all of the deposits have now been found in which the orebody, or the leached capping after ore, crops out. The deposits remaining to be found are those either completely covered by postmineral formations, or overlain by non-ore, premineral rocks, either in fault contact with ore or related to ore through vertical or lateral zoning relationships. Future discoveries will require greater use of indirect techniques—geologic projection, and geochemical and geophysical work, and perhaps most important, more exploration drilling per discovery, both in number of holes and average depth of holes. In a paper at the 1976 Annual AIME Meeting Schultz and Spat pointed out that the drilling cost per discovery has risen rapidly for the past several years.

Another factor which may loom larger than any other in the future is the question of the basic economics of porphyry copper mining in the Southwest. The price of copper in constant dollars diminished progressively during the period of 4000 B.C. to 1933, and then began to progressively increase. At the same time the minimum grade of ore which it was possible to mine progressively decreased from ancient times until the date of the most recent recession and the Middle East oil boycott and world energy crisis. Since that time the minimum minable ore grade has increased in both bulk underground, and open-pit copper mines. This trend could, of course, be reversed by a substantial increase in the price of copper, but this magnitude of increase is far from certain during the next few years. Most previous porphyry copper discoveries in the Southwest have been deposits which could be exploited as open pits. Most future discoveries will be potential underground mines, or in situ leaching situations. The ore habit in the Southwest favors deposits whose overall grade is less than 0.8% Cu. The San Manuel mine whose grade is about 0.72% Cu and 0.015% Mo could be taken as an example of the best type of deep, undiscovered deposit, which we are likely to find in the future. However, using current mining costs and present copper price a newly discovered, undeveloped San Manuel would not be a viable orebody. A copper grade of 0.9%-1.0% Cu, or a copper price of over $1.00 per pound would be required to make this hypothetical example a viable deposit. The increase in copper price is much more likely than finding the 1% plus copper deposit. If the price increase does not occur there will be few, if any, future discoveries of viable orebodies in the Southwest. Another effect of this factor is that there may be no longer be a tendency for known deposits to evolve into orebodies.

Exploration techniques which have been most successful in the Southwest have, as indicated by the tabulation, been geologic mapping and geologic interpretation, and leached capping interpretation. Geochemical and geophysical surveys have been of assistance in some discovery—the Pima orebody. Neither geochemical nor IP geophysical techniques are as effective in the Southwest as in western Canada and most other porphyry districts, because basin-range faulting has resulted in deep, postmineral valley fill; transported rath-

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[1] Banquet Address

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Table 1. United States tabulation of Southwest porphyry copper discoveries [1]

Porphyry Copper Deposit	*Date(s) Discovered*	*Published or Estimated Tonnage And Grade Prior To Production*[2]	*Distance from Known Porphyry Copper When Discovered*	*Percent Outcrop of Ore Body or of Ore Leached Capping*	*Percent Post Ore Cover Over Ore Body*	*Geochemical Anomaly Useful In Outlining Ore Body*	*Geophysical Anomaly Useful in Outlining Ore Body*
(1) San Manuel, Arizona	1917/1943	457,000,000 T 0.75 Cu	40 miles	± 5	± 95	Yes	Not used
(2) Safford-KCC, Arizona	1947/1955	500,000,000 T(+) 0.5(+) Cu	20 miles	30(?)	70(?)	Yes	Probably (IP)
(3) Tyrone, New Mexico	1920's/1950	±400,000,000 T 0.7 Cu	60 miles	±100	± 0	Yes	Probably not
(4) Pima, Arizona	1951	3,000,000 T(?) 0.5 Cu(?)	+60 miles	0	100	No	Yes (Magnetic)
(5) King Peak-Metcalf, Ariz.	1865/1952	±400,000,000 T(?) ±0.75 Cu(?)	1 mile	±100	± 0	Yes	Not used
(6) Imperial-Silver Bell, Ariz.	1909/1954	30,000,000 T(?) 0.75 Cu(?)	½ mile	± 10(?)	± 5	No	No
(7) Mission, Arizona	1954	200,000,000 T(+) ±0.75 Cu	1 mile	0	100	No	Uncertain
(8) San Xavier North, Ariz.	1955/1957	100,000,000 T(+) 0.5(+) Cu	2 miles	1(?)	99	No	Probably not
(9) Esperanza, Arizona	1955	150,000,000 T 0.68 Cu equiv.	8 miles	100	0	Yes	Uncertain (IP)
(10) Christmas, Arizona	1870/±1955	100,000,000 T(+) 0.4(+) Cu	15 miles	± 40	± 60	Yes	Uncertain (IP)
(11) Twin Buttes, Arizona	1957/1963	530,000,000 T(?) ±0.70 Cu	5 miles	0	100	No	Mag. trend hlpfl.
(12) Dos Pobres (P.D.), Safford, Arizona	1957	400,000,000 T(+)(?) 0.72 Cu(?)	±3 miles	± 25	± 75	Yes	Yes (IP)
(13) Ithica Peak, Arizona	1959	175,000,000 0.53 Cu	90 miles	±100	± 0	Yes	Possibly (IP)
(14) Sierrita, Arizona	1960/1963	±450,000,000 0.45 Cu equiv.	1½ miles	± 90	± 10	Yes	Probably (IP)
(15) East Helvetia (Rosemont), Arizona	1961	200,000,000 T(+) 0.7 Cu (?)	15 miles	± 10(?)	± 30(?)	Yes	Possibly (IP)
(16) Sacaton, Arizona	1961	±50,000,000 T 0.8(+) Cu	15 miles	0	100	No	No
(17) Battle Mtn., Nevada	1869/1961	50,000,000 T(+) 0.5(+) Cu	145 miles	±100	± 0	Probably	Uncertain
(18) Kalamazoo, Arizona	1965	500,000,000 T(+) 0.73 Cu	½ mile	0	± 50	Yes	Not used
(19) Vekol, Arizona	1965	75,000,000 T(?) 0.5(+) Cu(?)	±30 miles	0	90	No	Uncertain (IP)
(20) Copper Creek, Arizona	1966	50,000,000 T(+) (?) 0.7(+) Cu(?)	15 miles	0	0	No	Probably not (IP)
(21) Caridad, Mexico	1967	600,000,000 T 0.8 Cu	70 miles	100	0	Uncertain	Uncertain(IP)
(22) Copper Basin, Arizona	1920/1968	100,000,000 T(+) ±0.6 Cu eq.	35 miles	± 70	± 30	Yes	Probably (IP)
(23) Lakeshore, Arizona	1955/1968	472,000,000 T 0.76 Cu(?)	10 miles	± 10	± 90	Probably	Uncertain (IP)
(24) Poston Butte-Florence, Az.	1961/1970	400,000,000 T(?) 0.45 Cu(?)	±25 miles	0	100	No	Probably not (IP)
(25) Red Mountain, Ariz.	1970	ND	30 miles	0	0	Yes	No
(26) Hillsborough, N.M.	1930/1975	70,000,000 T(?) 0.7 Cu(?)	±40 miles	60	40	Yes	Uncertain (IP)

1. Includes Caridad (No. 21) in Mexico. 2. (?) Indicates uncertain data with only order-of-magnitude accuracy.

[1] Reprint from World Mining, 1976, v. 29, no. 11, by permission of the author.

Table 1. United States tabulation of Southwest porphyry copper discoveries—continued

Apparent Discovery Method	*Porphyry Copper Deposit*	
Geologic mapping and structural interpretation indicated that a small outcrop could expand downward into a large orebody	San Manuel, Arizona	(1)
Geologic mapping and interpretation of peripheral hydrothermal effects encouraged testing through postore volcanics	Safford-KCC, Arizona	(2)
Sampling and leached capping study. An old, higher grade underground mine evolved into a bulk low grade open pit	Tyrone, New Mexico	(3)
Geophysical survey on geologic projection located high magnetite skarn under postmineral gravel	Pima, Arizona	(4)
Leached capping interpretation and sampling indicated chalcocite orebody	King Peak-Metcalf, Arizona	(5)
Geologic interpretation and research of old mine records indicated possible hidden orebody	Imperial-Silver Bell, Arizona	(6)
Geologic interpretation and research of nearby mine openings and outcrop indicated possible extension of zone of alteration-mineralization at Pima	Mission, Arizona	(7)
Aerial reconnaissance located small outcrop of leached capping, and orebody found with offset drilling	San Xavier North, Arizona	(8)
Geologic mapping and leached capping study	Esperanza, Arizona	(9)
Sampling and geologic interpretation of old mineral prospect	Christmas, Arizona	(10)
Geologic interpretation based partly on magnetics, followed by wide-spaced offset drilling	Twin Buttes, Arizona	(11)
Geologic and leached capping interpretation of unusual outcrop and geochemical survey	Dos Pobres (P.D.), Safford, Arizona	(12)
Geologic and leached capping interpretation of old mineral prospect	Ithica Peak, Arizona	(13)
Geologic mapping and test drilling—old prospect evolved into orebody in part due to shifting economics	Sierrita, Arizona	(14)
Geologic and leached capping interpretation of old mineral prospect	East Helvetia (Rosemont), Arizona	(15)
Geologic reconnaissance program located small outcrop interpreted to be pyritic capping peripheral to orebody	Sacaton, Arizona	(16)
Old deposit which evolved into an orebody with geologic mapping, drilling and improvement in economics	Battle Mtn., Nevada	(17)
Geologic mapping and interpretation of structure and concentric zoning	Kalamazoo, Arizona	(18)
Geologic mapping and IP survey	Vekol, Arizona	(19)
Geologic interpretation of surface geology and re-interpretation of previous drilling	Copper Creek, Arizona	(20)
Leached capping and geologic interpretation	Caridad, Mexico	(21)
Geologic mapping and test drilling. Old prospect evolved into orebody	Copper Basin, Arizona	(22)
Geologic mapping and drilling done near fault segment orebody. Also IP survey	Lakeshore, Arizona	(23)
Geologic interpretation of peripheral outcrops followed by wide-space offset drilling	Poston Butte-Florence, Arizona	(24)
Geologic interpretation of vertical zoning followed by deep drilling	Red Mountain, Arizona	(25)
Geologic interpretation of previous drill data	Hillsborough, New Mexico	(26)

er than residual soils; and typically thick leached and oxidized zones which do not give an IP response. Both the IP and geochemical methods are best suited to a British Columbia environment of near-surface sulfides and shallow cover. As Southwest exploration progresses into deeper and deeper postmineral cover these methods will also tend to become less effective unless new and more reliable techniques can be developed.

The tabulation of discoveries indicates that seven of the last eleven deposits were essentially completely covered (one, Lakeshore, had 10 percent outcrop), and that since 1960, seven of the ten discoveries in Arizona have been completely covered. The percentage of covered discoveries is certain to increase in the future.

Reviewing some of the other factors on the tabulation we see that there were ten deposits discovered in the period 1943-1955, nine deposits discovered from 1955-1965, and seven deposits discovered after 1965. This suggests a progressive decrease in the success rate. It should be noted that many of the deposits have multiple discovery dates which reflect an earlier intersection of the mineralized body, and a later decision that it may represent a minable deposit—often by a different company. There seems to be no consistent variation in size of the deposits through the 33-year period, nor is there a noticeable change in the distance from a known porphyry. As mentioned, the amount of postmineral cover over discoveries has progressively increased through the period. Geochemical surveys appear to have been somewhat more useful than geophysical surveys, although geochemistry has never been the principal factor in a discovery as was the case for the Pima magnetometer survey. Geophysical surveys also have had some useful depth-of-cover and groundwater applications.

It's interesting to note that one orebody was found in an old company file cabinet, and one deposit was found by a re-interpretation of old drill data. Zoning interpretations and offset drilling are mentioned more frequently toward the bottom of the table as no more ore outcrops remain to be tested. Also almost every deposit was specifically discovered by a drill hole—whether drilled for the right reason or the wrong reason. There would have been very few discoveries without the drill rig, and the programs which never progressed from the "think stage" to the "drilling stage" were invariably doomed to failure.

It would perhaps be useful to select three deposits representative of the three decades covered by the tabulation and describe each to illustrate changes in settings and in successful exploration techniques over this period.

The first example is King Peak—Metcalf, immediately east of the Morenci—Clay orebody. This exploration target was identified in a careful and accurately interpreted leached capping study completed in 1952, and the first exploration hole intersected ore. The pre-discovery drilling cost of the project was very low. Tyrone would be a similar example, but no targets of this type now remain untested in the United States, although there may still be a few in Latin America and Iran and Pakistan.

The second example is the Sacaton deposit found near Casa Grande, Arizona in 1961. This discovery was one of several Asarco finds which resulted from a comprehensive district-wide program of geologic mapping in southern Arizona of features related to porphyry copper mineralization. This regional work tended to bridge the gap between theoretical and applied geology, particularly in the areas of stratigraphic and structural interpretation. Several holes at Sacaton were initially drilled as offsets around a small outcrop identified as being pyritic, but probably porphyry-copper-related, leached capping, before ore was intersected. Many additional drill holes were required before a viable orebody was confirmed, and the overall ratio of development drill footage to tons of ore developed was also high.

The third example is the Red Mountain deposit near Patagonia, Arizona, discovered in 1970, and described in a recent Economic Geology paper by Russ Corn. This is the deepest porphyry which has so far been found. It is in an area of premineral outcrop where shallow, sub-commercial mineral deposits have been known for many years. Discovery of the deep deposit resulted from persistent and thoughtful exploration to progressively deeper depths over a period of 12 years. The key to the discovery was vertical hydrothermal zoning theory. The pre-discovery driling expense was very large, and post-discovery drilling and development expense will be very large.

The conclusion from this review must be that deposits are becoming harder and more expensive to find. Most of our exploration tools become less effective with increase in thickness of postmineral cover. Recent shifts in copper economics have been a further obstacle; however, copper exploration, like the copper market, has always been a cyclic field, and many additional deposits remain under the Tertiary gravel and volcanics which will probably be discovered in the next 30-year period.