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

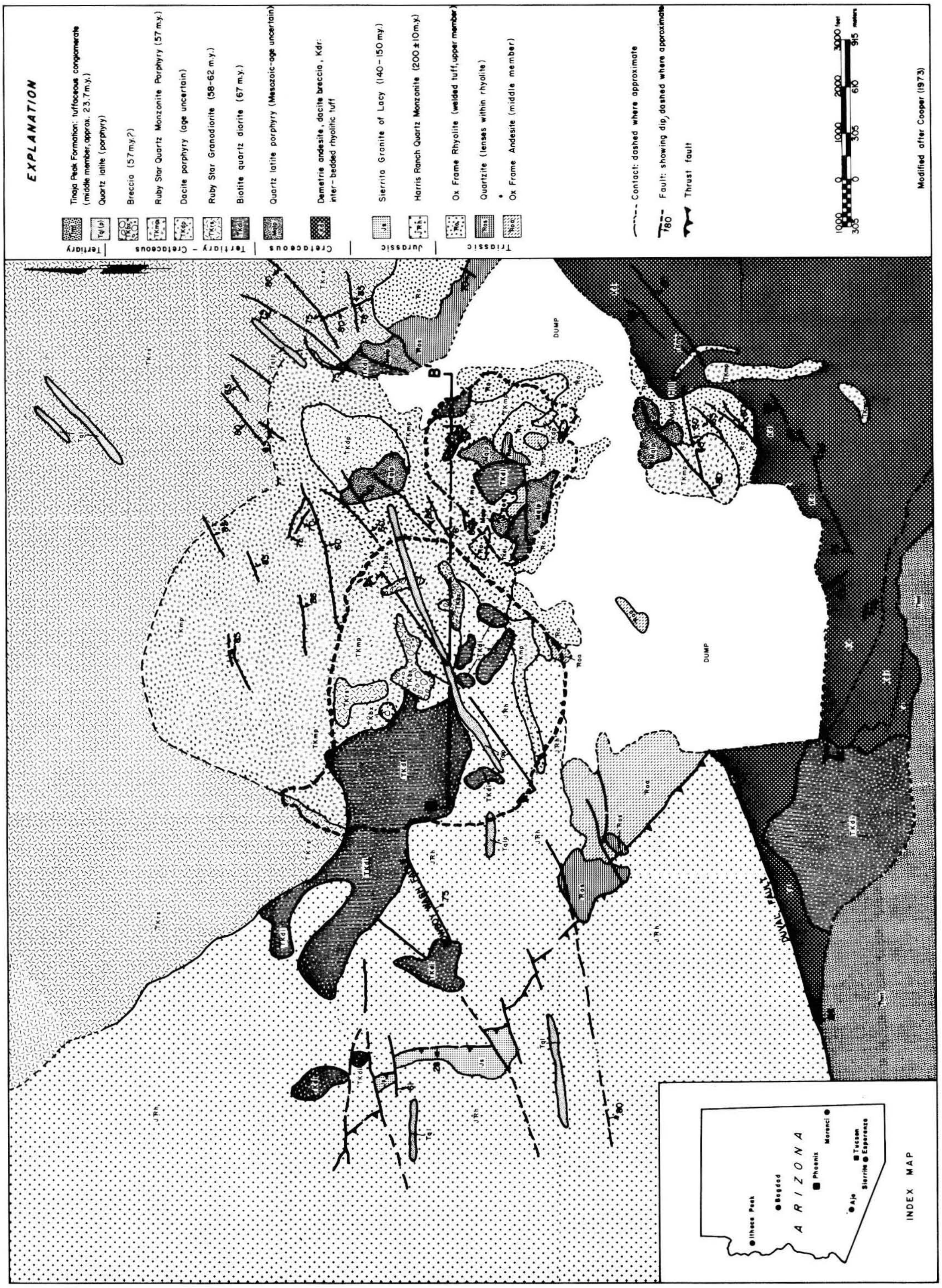

Fig. 1. Geologic map of Sierrita-Esperanza deposit—modified from Cooper (1973)

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.

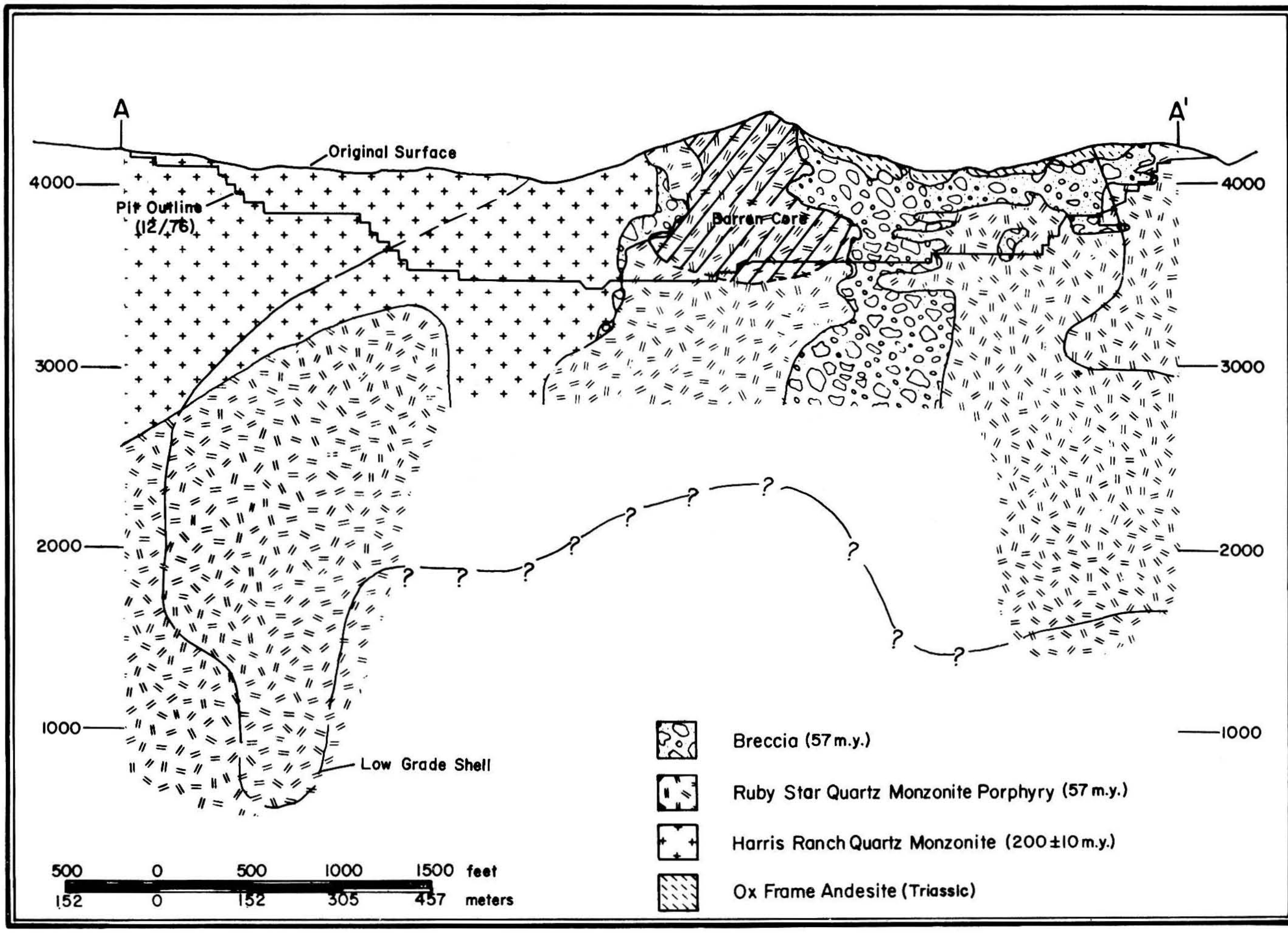

Fig. 2. Section A-A', showing Sierrita geology

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-

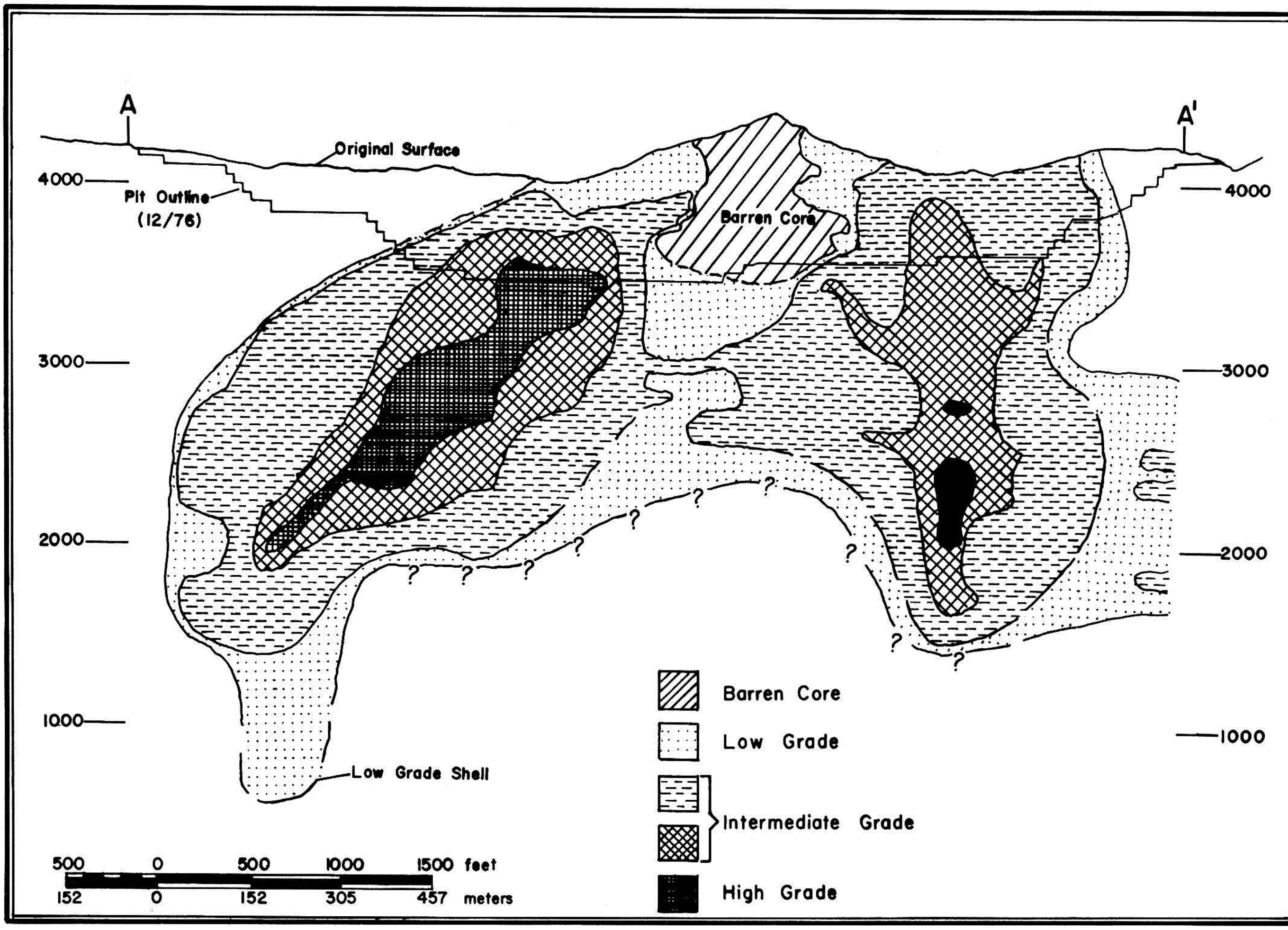

Fig. 3. Section A-A', showing distribution of economic mineralization at Sierrita

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

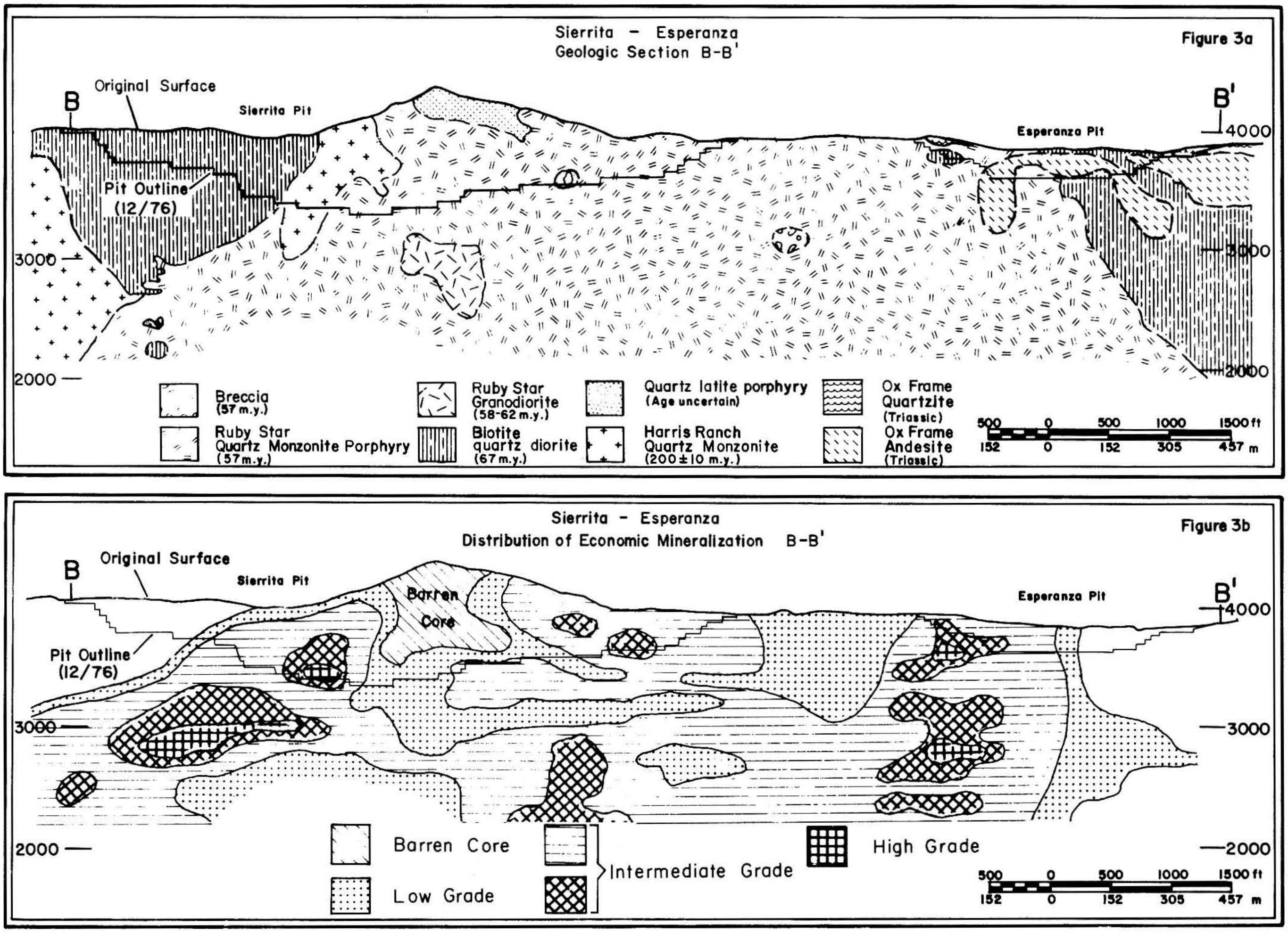

Fig. 4. Section B-B': (a) Geology of the Sierrita-Esperanza deposit; (b) distribution of economic mineralization

(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-

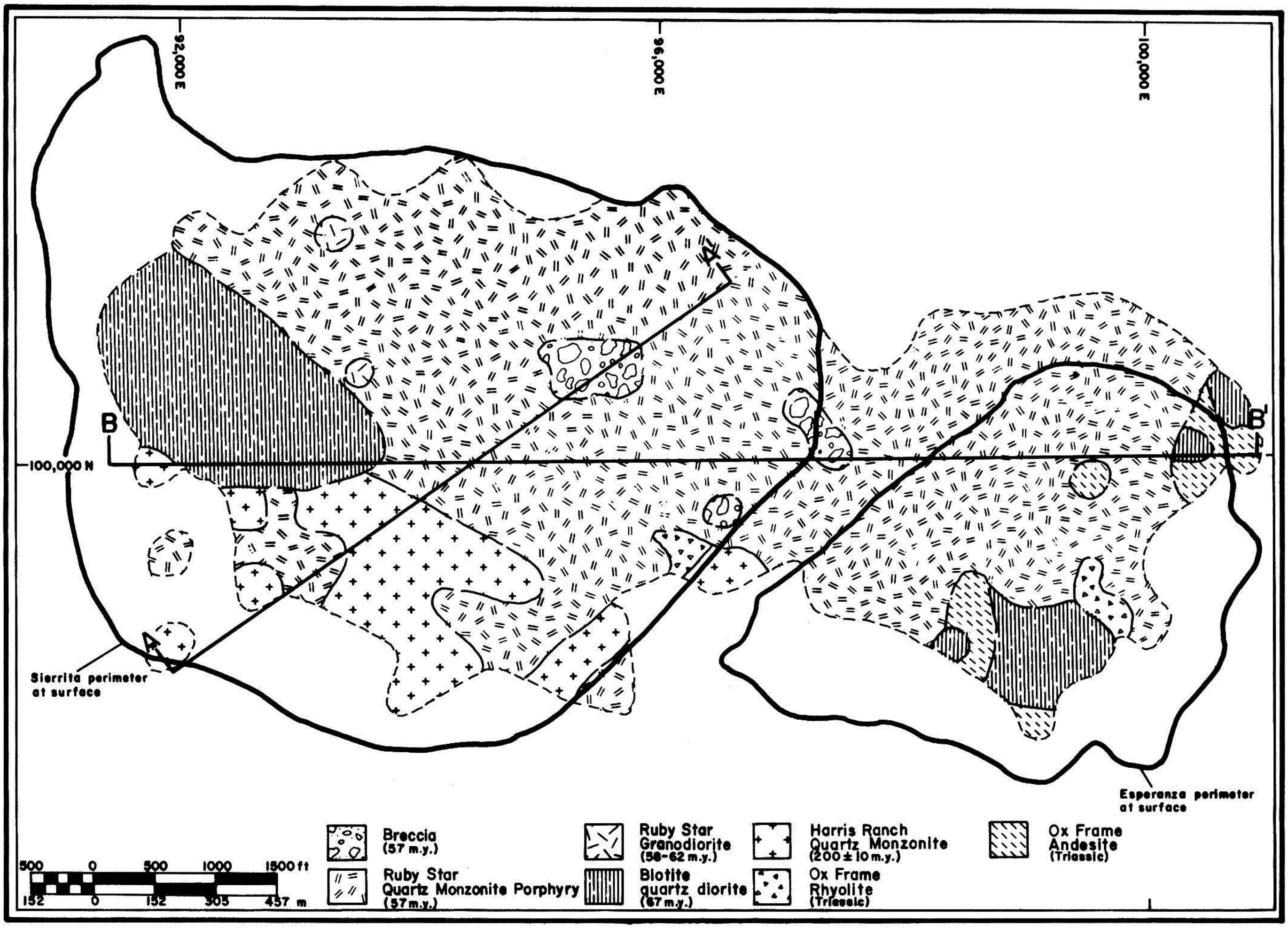

Fig. 5. 3200 bench, showing Sierrita-Esperanza deposit geology

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

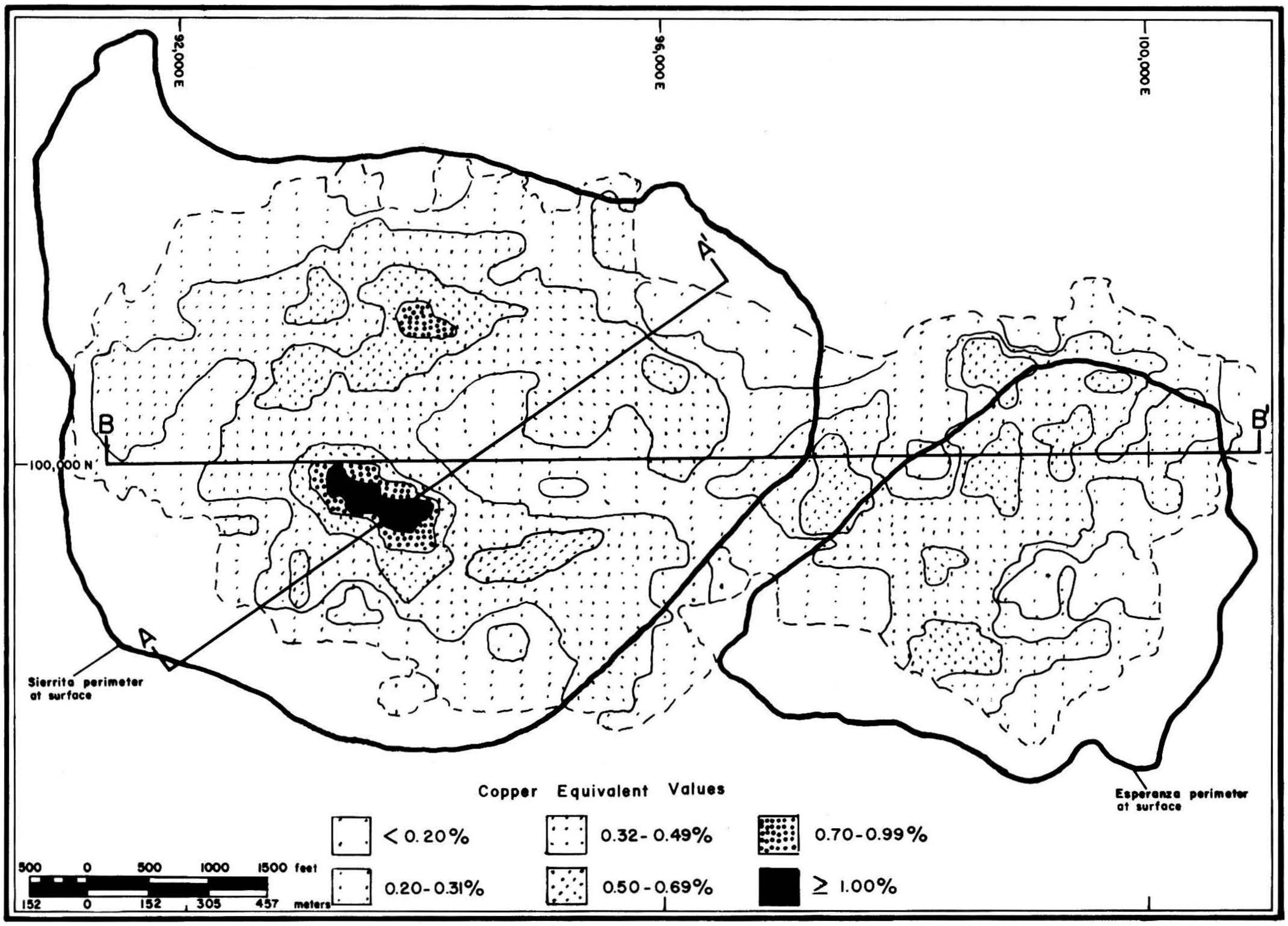

Fig. 6. 3200 bench, showing distribution of mineralization at Sierrita-Esperanza

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, mineralization 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.

Acknowledgments

Acknowledgment is due the following individuals for their advice, constructive criticism, and assistance in the preparation of this paper: Dr. John I. Sharpe, General Manager—Exploration, Duval Corporation; Mr. Robert A Metz, District Geologist, Duval Corporation; Mr. Kenneth L. Lamb, Manager—Mining, Duval-Sierrita Corporation; Mr. Calvert D. Iles, Mine Engineer, Duval-Sierrita Corporation; Mr. Jerry C. Morgan, Geologic Draftsman, Duval-Sierrita Corporation.

Special thanks are given to the previous members of the Sierrita and Esperanza geology staff for their accumulated data and ideas that formed the basis for much of the material presented in this report. In particular, we wish to thank Messrs. Dean W. Lynch, Robert A. Metz, Calvert D. Iles, Chester A. Oakley, A. Harvey James, and Frank Mack.

We express our appreciation to Mr. Harry L. Shively, General Manager, Duval-Sierrita Corporation, and to Duval Corporation for permission to prepare and publish this paper.

References

Anderson, C. A., and Kupfer, D. H., 1944, Report of the properties of the Amargosa Molybdenum and Copper Corporation, Pima County, Arizona: U.S. Geol. Survey Strategic Minerals Inventory.

Cooper, J. R., 1971, Mesozoic stratigraphy of the Sierrita Mountains, Pima County, Arizona: U.S. Geol. Survey Prof. Paper 658-D.

______1973, Geologic map of the Twin Buttes quadrangle, southwest of Tucson, Pima County, Arizona: U.S. Geol. Survey Misc. Geol. Inv. Map I-745.

Creasey, S. C., and Kistler, R. W., 1962, Age of some copper-bearing porphyries and igneous rocks in southeastern Arizona: U.S. Geol. Survey Prof. Paper 450-D, p. D1-D5.

Damon, P. E., and associates, 1965, Correlation and chronology of ore deposits and volcanic rocks. U.S. Atomic Energy Comm. Ann. Rept. No. COO-689-50: Tucson, University of Arizona.

______1966, Correlation and chronology of ore deposits and volcanic rocks. U.S. Atomic Energy Comm. Ann. Rept. No. COO-689-60: Tucson, University of Arizona.

Damon, P. E., and Mauger, R. L., 1966, Epeirogeny-orogeny viewed from the Basin and Range province: Soc. Mining Engineers Trans., v. 235, no. 1, p. 99-112.

Guilbert, J. M., 1977, Personal communication: Dept. of Geosciences, University of Arizona.

Iles, C. D., 1973, Mineralization control at the Duval-Sierrita property, Pima County, Arizona: unpublished report, Duval-Sierrita Corporation, Sahuarita, Arizona.

Lovering, T. G., Cooper, J. R., Drewes, Harald, and Cone, G. C., 1970, Copper in biotite from igneous rocks in southern Arizona as an ore indicator: U.S. Geol. Survey Prof. Paper 700-B, p. B1-B8.

Lowell, D. J., and Guilbert, J. M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Econ. Geology, v. 65, no. 4, p. 373-408.

Lynch, D. W., 1967, The geology of the Esperanza mine and vicinity, Pima County, Arizona: unpublished M.S. thesis, Dept. of Geology, University of Arizona, Tucson.

Oakley, C. A., 1973, A synopsis of alteration and mineralization at the Sierrita and Esperanza mines: unpublished report, Duval-Sierrita Corporation, Sahuarita, Arizona.

Pennzoil Company, 1974, Annual report: Houston, Texas.

Rehrig, W. A., and Heidrick, T. L., 1972, Regional fracturing in Laramide stocks of Arizona and its relationship to porphyry copper mineralization: Econ. Geology, v. 67, p. 198-213.

Schmitt, H. A., Clippinger, D. M., Roper, W. J., and Toombs, H. B., 1959, Disseminated deposits at the Esperanza mine, in Heindl, L. A. (ed.), Southern Arizona Guidebook II: Tucson, Arizona Geological Society, p. 205-206.

Smith, V. L., 1975, Hypogene alteration at the Esperanza mine, Pima County, Arizona: unpublished M.S. thesis, Dept. of Geology, University of Arizona, Tucson.

Titley, S. R., 1975, Geologic characteristics and environment of some porphyry copper occurrences in the southwestern Pacific: Econ. Geology, v. 70, p. 499-514.