# GEOLOGICAL INTERPRETATION OF THE PALO VERDE MINE BASED UPON DIAMOND DRILL CORE[1/]

By

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## INTRODUCTION

The Palo Verde mine, owned and operated by the Banner Mining Company, Tucson, Arizona, is located in the Pima mining district, Pima County, Arizona, approximately 20 miles south of Tucson along the Twin Buttes Road. The mine is bounded on the north by the San Xavier Papago Indian Reservation and on the west by Banner's Mineral Hill-Daisy area. The general locale of this mining area is the gently sloping alluvium-covered pediments on the northeast flank of the Sierrita Mountains. The alluvial covering averages 200 feet in the vicinity of the shaft, and the closest bedrock outcrops approximately 4, 200 feet to the southwest. The elevation above sea level at the Palo Verde shaft collar is 3, 242 feet. This mine is relatively new, and thus there has been only a limited amount of exploration and development from which data may be obtained for geological study. This paper was written almost entirely on the strength of the geologic interpretation based upon diamond-drill holes, which have been spaced 250 feet apart in an equilateral triangular grid system.

During September 1959, a 5-compartment steel and concrete shaft was started. Prior to the shaft sinking, a churn hole was drilled 35 feet to the south of the shaft, and no water was hit until the hole reached below the 1, 100-foot level. Shaft sinking progressed fairly rapidly in relatively dry ground until a large flow of water was tapped at the 960-foot level. Stations have been cut at the 700-, 800-, and 900-foot levels, and future expansion below these is planned.

A thousand ton per day production is anticipated and work is now in progress underground on all levels according to schedule. Diamond drilling is still being utilized, as the outer limits of the Palo Verde orebody have not yet been delineated in all directions. Approximately 40, 000 feet of diamond drilling plus several thousand feet of churn drilling have constituted the exploration and development program in this area.

## ROCKS

The basement complex in this area is presumably the Precambrian(?) "Sierrita" Granite, which is an unmineralized and slightly chloritized light-

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greenish-gray, medium- to coarse-grained granite. It is exposed on the surface 1-1/2 miles to the west of the Palo Verde shaft and in the bottom of several diamond-drill holes in the vicinity of the shaft. The surface of the granite dips uniformly at low angles to the north and east in the area.

In addition to the Sierrita Granite, other intrusives, such as quartz monzonite porphyry and andesite dikes, are found in the area. The intruded host rocks are limestones and quartzites of Paleozoic age, and arkose, graywacke, and argillite of Cretaceous age.

The quartz monzonite porphyry consists of quartz, feldspar, and biotite mica, mineralized with varying amounts of pyrite, chalcopyrite, and molybdenite. The size of the feldspar phenocrysts ranges from microscopic to a quarter of an inch; an occasional pink phenocryst measures as much as three-fourths of an inch in length. The feldspar phenocrysts comprise approximately 60 percent of the porphyry. The biotite mica flakes are small and sparsely disseminated through the porphyry. Gypsum is prevalent throughout as small veinlets and coatings on the exposed surfaces in the fractures. The porphyry has been extensively crisscrossed with small, 1/16- to 1/2-inch veinlets of "late" quartz usually containing pyrite and molybdenite. The porphyry forms a massive sill-like body somewhat anticlinal in nature having its axis plunging to the west at a low angle. This sill is very extensive in areal coverage, and a more detailed discussion of it is beyond the scope of this paper. A major portion of the top of the porphyry sill and related orebodies have been removed by erosion. Numerous small, fingerlike apophyses protrude from the mass into the sedimentary host rocks.

The andesite is in the form of relatively thin dikes that intrude the limestone and arkose east of the shaft, but no such intrusion has been observed in the quartz monzonite porphyry. The dikes are no doubt post-mineralization in age, but their age in relation to the thrusting is unknown as yet.

The sedimentary rocks have been recrystallized and hydrothermally altered so that the original character is fairly uncertain. It appears that only the Paleozoic and Cretaceous(?) rocks are represented in the immediate area of the Palo Verde mine.

The Paleozoic rocks are limestones, quartzite, marl, gypsum, and hornfels. The limestone is gray to blue, fine grained, impure, and partly recrystallized. Associated with the limestone are lenses of relatively pure quartzite suggestive of the Permian Scherrer Formation. The topmost portion of the limestone has been largely altered to tactite, whereas the lower portion has been recrystallized to marble. Underlying the limestones and quartzite are faulted slivers of the Pennsylvanian hornfels and the Permian marl and gypsum beds. Gypsum from these lower beds has been dissolved and carried both laterally and upward into overlying formations. The reasons for stating that the gypsum came almost entirely from the underlying gypsiferous sedimentary beds rather than from the oxidation of pyrite are as follows: (1) an abundant supply of gypsum is present below; (2) the water has a hydrostatic head; and (3) the gypsum is prevalent in all rocks below a certain undulating horizon and is almost entirely absent above. It is assumed that the large amounts of extremely hard water tapped in the Palo Verde shaft and drill holes followed extensive water courses in the gypsiferous beds and limestones.

Resting unconformably on the Paleozoic formations are units of presumably Cretaceous arkose, graywacke, and argillite interbedded with thin lenses of tactite and conglomerate. All these units have been acceptable to mineralization with the exception of the dense compact siltstone.

## STRUCTURE

The true structural conditions prevailing at the Palo Verde mine area are not entirely decipherable from the limited amount of information revealed by drill holes. Certain indisputable structural relationships, however, do exist, and from these a reasonable geologic picture can be pieced together.

A low-angle thrust fault separates the Precambrian(?) Sierrita Granite from the overlying porphyry and sedimentary formations. Typical of most thrusts, a gouge and brecciated zone as much as 16 feet in thickness has been found whenever drilling penetrated the fault. The gouge is usually gray to green gray, containing small subangular to rounded fragments with no discernible mineralization. The overlying competent rocks are intensely fractured as much as 50 feet above the fault surface.

There are reasons to believe that this major thrust fault is the same one that Cooper (1960) has named the "San Xavier thrust," and which he predicts has lateral movement up to 6-1/2 miles. If Cooper's hypothesis is correct, then the roots of the Palo Verde and adjoining orebodies are in the Twin Buttes area. There are corresponding similarities which lead the writer of this paper to agree with Cooper. Thrusting and normal faulting definitely occurred at two and possibly more intervals of time. The pre-mineral faulting was probably relatively steep dipping, and it was here in these zones of weakness that the mineralization took place.

Post-mineral faulting is apparent underground; both thrusts and northeasterly shears cut off and displace the orebodies. The faulting above the San Xavier thrust was complimentary to it and of relatively small magnitude. In the east Palo Verde area, steep-dipping shears served also as channelways for the late andesite dikes to follow. Minor bedding plane slips, small thrust faults, and local rolls along the bedding are indicative of previous compressional stresses in the area. The abundant steeply dipping quartz and sulfide veinlets in the quartz monzonite porphyry also indicate pre-mineral fracturing. Lack of adequate drill-core information prohibits the interpretation of any definite fracture pattern in the area, but future underground developments will no doubt disclose one or more patterns.

## ALTERATION

Alteration of the rocks in the Palo Verde area has been very intense; hardly any remain that did not undergo the hydrothermal processes of recrystallization and metasomatism. Alteration is more pronounced in the vicinity of the intrusive porphyry sill but extends well beyond the boundaries of the Palo Verde area. The zones of alteration in respect to their spatial relationship to the porphyry are: (1) kaolinization; (2) silicification, pyritization; and (3) recrystallization of the limestones.

In the quartz monzonite porphyry, hydrothermal alteration has kaolinized more than 75 percent of the feldspars and biotite mica. Quartz and small quantities of sericite also resulted from this alteration. The crystal structure of the quartz phenocrysts mostly has been obliterated by resorbtion of the silica. The twinning planes and crystal faces of the feldspars are also obscured by the alteration processes. Sericite and chlorite are present in the porphyry in such small, scattered amounts as to be of minor importance. In the sedimentary rocks, particularly in the graywacke and arkose adjacent to the porphyry, secondary feldspars have been formed. The arkoses and graywacke have been extensively epidotized, and wherever encountered the epidotization is intense, the pyrite content of the rock increases.

In the tactite-garnet zone at the Palo Verde, the alteration products are garnet, clay garnet, hematite, chlorite, and pyroxenes such as diopside and wollastonite. The clay garnet is undoubtedly the product of some brecciation and hydrothermal alteration of the garnet and epidote rocks. It consists of small rounded and subangular fragments of garnet and epidote in an argillaceous matrix; chalcopyrite and bornite appear as small blebs throughout. The unaltered garnet rock is reddish brown to dark green, dense, and extremely hard. The chalcopyrite and bornite favor this rock, particularly in its lower limits that approach the calcium silicate zone, where the predominant silicate minerals are diopside, wollastonite, and tremolite.

In the calc-silicate zone, dark-brown to black sphalerite predominates, intermixed to some extent with bornite and chalcopyrite. Wherever chalcopyrite is found with the sphalerite, it is usually speckled throughout the latter in small blebs. The sphalerite usually serves as a line of demarcation between ore and waste. Small amounts of it are found in the marbleized limestone isolated from the orebodies by waste. The limestone grades from the calc-silicate zone into barren marble and bleached limestone, then into gray-white unaltered limestone where a few unrecognizable fossils are present. Graphite is rare but does occur in the limestone in association with a fault zone.

Minor bleaching and alteration of the host rocks are found where the late andesite dikes have intruded. These andesite dikes are unmineralized, definitely being post-mineralization, but whether they are pre- or post-thrusting is problematical, and a determination of this point cannot serve any useful geologic purpose.

## ORE DEPOSITS

The known ore deposits in the Palo Verde mine area are classified as pyrometasomatic in type, occurring in the limestones and contact silicate zones as replacements and in the porphyry, arkose, and related clastic rocks as disseminations. The mineralizing solutions appear to have entered the rocks from the south and west in proximity to the porphyry. This assumption is based primarily on the zonal arrangement of the mineral assemblage. The higher grade orebodies formed in the tactite, below the quartzite, in gentle rolls plunging downward to the north and northwest on dips ranging from $24^{o}$ to $42^{o}$.

At the Palo Verde mine there are two types of orebodies, the first and most extensive being the lower grade disseminated type, and the second, of considerably higher grade, being located in the tactite zone. Although directly related to the mineralization, the quartz monzonite porphyry contains no appreciable amounts of copper sulfides. The bulk of the sulfide mineralization in the porphyry is iron pyrite; the chalcopyrite averages less than ore grade.

Molybdenite mineralization is confined almost entirely to the porphyry and quartzite, which suggests that the more acid rocks provide a favorable environment for the mineralizing solutions.

A definite relationship exists between the intrusives and the orebodies in the intruded host rocks. As distance from the quartz monzonite contact increases, the degree of metamorphism and intensity of mineralization decreases. Paragenetically the minerals appear to be related in the following manner.

Silicate minerals developed early in the alteration process; the sulfide minerals were deposited last and replaced the silicate minerals in part. Apparently some recrystallization of the silicate minerals took place during the time of sulfide deposition.

Two or more stages of mineralization are associated with the porphyry intrusion and are pre- "San Xavier" thrusting in age. The first stage introduced the bulk of the ore minerals, whereas the second or later stages formed the small veinlets of quartz, pyrite, and molybdenite.

Mineralization is intense in the more favorable tactite zone where the higher grade of ore is associated with the iron-rich reddish-brown garnet rock. The paragenetic sequence and spatial relationship outward from the intrusive quartz monzonite porphyry consists of pyrite, molybdenite, chalcopyrite, bornite, argentiferous tennantite, and sphalerite. Magnetite is conspicuously absent in this immediate area but is abundant on the south flank of the quartz monzonite porphyry sill in the Daisy mine. A small (6-inch) vein of argentiferous tennantite and quartz cutting the porphyry was discovered in the shaft at the 350-foot level, but most of the tennantite is found in the lower tactite zone intermingled with the bornite and sphalerite.

## OXIDATION AND ENRICHMENT

The zone of oxidation and secondary enrichment in the Palo Verde area averages 30 feet in thickness and has a maximum thickness of 70 feet. The deepest supergene sulfides bottomed at 382 feet below the ground surface. The lack of an appreciable blanket of enriched chalcocite indicates that leaching and migration of copper from the oxide zone were absent. Small amounts of copper oxides were found in the caliche capping immediately above the orebody, indicating a slight upward migration of the copper.

The principal minerals resulting from the oxidation and enrichment are chrysocolla, chalcocite, and various iron oxides. Malachite and azurite have been noted only rarely in this zone. In the lower portion of the oxidized zone, black copper oxides are not too infrequently found immediately above the chalcocite-coated pyrites of iron and copper. A relatively sharp line of demarcation is formed by the chalcocite with the underlying hypogene sulfides.

Oxidation has obliterated the original texture and characteristics of the rock types found in the upper portions of the oxide zone. The lack of oxides at depth in any of the intensely fractured rocks indicates that the supply of oxygen was cut off at a very definite and uniform limit. This is suggestive of the permanent ground-water level at the time prior to the formation of the caliche conglomerate capping.

## CONCLUSION

Pending underground development and confirmation of the geologic picture, as represented here by drill cores, it appears that the following conclusions and predictions can be made:

1. Chemical favorability rather than structure was the controlling factor in the localization of the orebodies.

2. The higher grade orebodies can be located by using as recognition criteria wall-rock alteration and the zonal arrangement of the ore minerals.

3. The bottom of the orebodies can be expected once the sphalerite zone is reached.

4. Additional high-grade orebodies will be found in the tactite zone beneath the porphyry sill.

## ACKNOWLEDGMENT

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## REFERENCES

Cooper, J. R., 1960, Some geologic features of the Pima mining district, Pima County, Arizona: U.S. Geol. Survey Bull. 1112-C, p. 63-103.

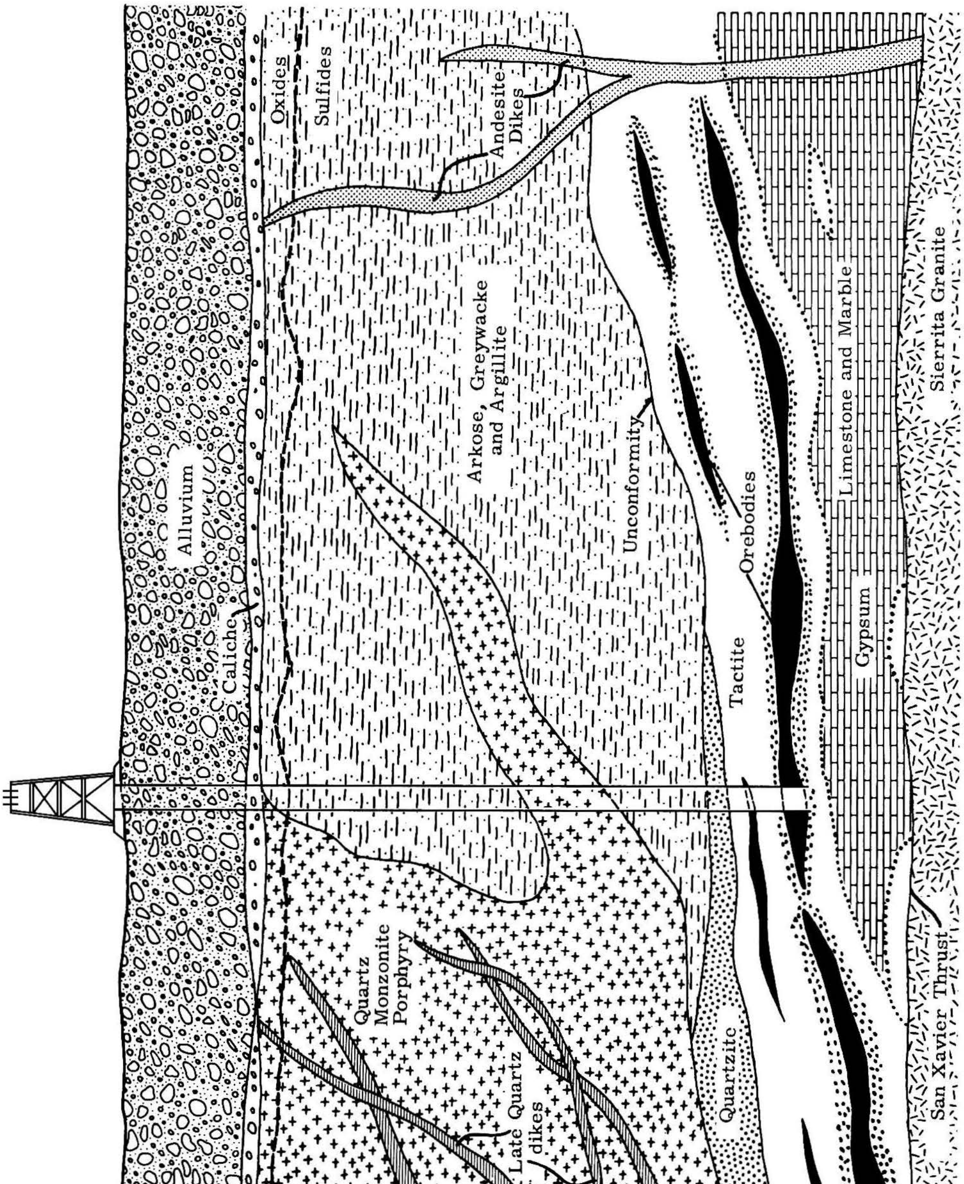
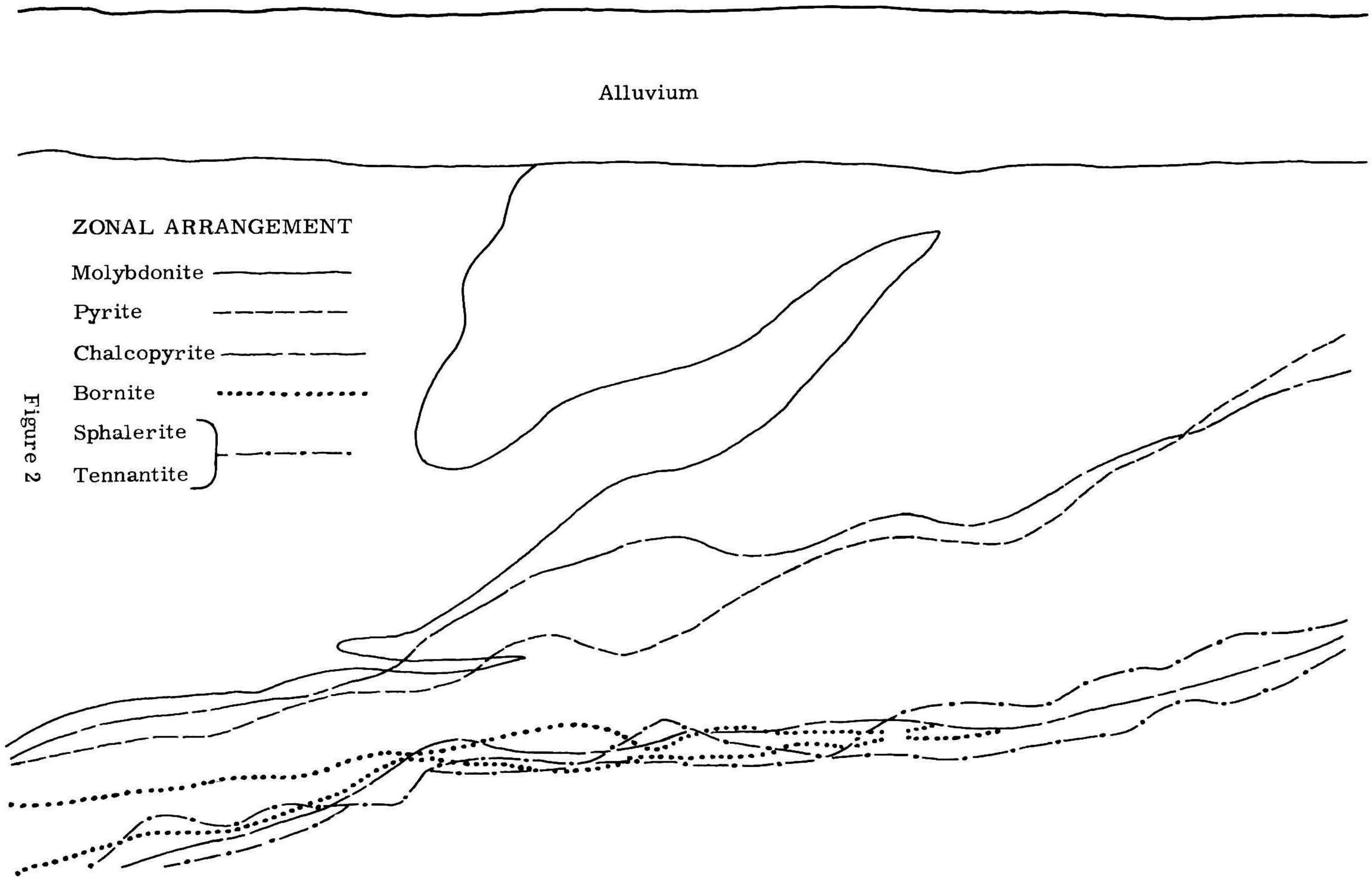

Alluvium
Caliche
Oxides
Sulfides
Andesite Dikes
Arkose, Greywacke and Argillite
Unconformity
Orebodies
Tactite
Limestone and Marble
Gypsum
Sierrita Granite
San Xavier Thrust
Quartzite
Quartz Monzonite Porphyry
Late Quartz dikes

Figure 1



Alluvium
ZONAL ARRANGEMENT
Molybdonite
Pyrite
Chalcopyrite
Bornite
Sphalerite
Tennantite


Figure 2