

Geology of the
San Manuel
Copper Deposit
Arizona

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By GEORGE M. SCHWARTZ

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GEOLOGY OF THE SAN MANUEL COPPER DEPOSIT, ARIZONA

By GEORGE M. SCHWARTZ

ABSTRACT

The San Manuel copper deposit is in the Old Hat mining district, Pinal County, Ariz. It is 35 miles northeast of Tucson and about a mile south of Tiger where the St. Anthony mine produced gold, molybdenum, vanadium, lead, and zinc.

In 1942, Henry W. Nichols, one of the owners of the San Manuel claims, applied to the Reconstruction Finance Corporation for a development loan. In turn, the War Production Board was informed of the application, and it requested the U. S. Geological Survey to examine the claims and report on the possibilities of quick production of copper by shovel operations and leaching vats. N. P. Peterson and B. S. Butler of the Geological Survey examined the property and recommended more exploration. The U. S. Bureau of Mines drilled a total of 17 holes which established the existence of the copper deposit. The Bureau discontinued work in 1945 when the Magma Copper Company obtained an option on the property. Adjacent ground was also drilled by the Houghton Group, a unit of the Anaconda Copper Mining Company.

Relatively few rock formations are exposed in the area. From oldest to youngest these consist of quartz monzonite and aplite, monzonite porphyry, diabase, lava flows, rhyolite and rhyolite breccia, Gila (?) conglomerate, alluvial slope deposits, and Recent alluvium of the dry washes.

The oldest formation is quartz monzonite (Oracle granite) of pre-Cambrian age and is part of a granite mass that occupies a large area on the north slope of the Santa Catalina Mountains. Fine-grained aplite dikes cut the coarse-grained porphyritic facies.

Intruded monzonite porphyry forms irregular masses in the quartz monzonite and is the predominant rock in the eastern part of the mineralized area. The porphyry is much finer grained than the quartz monzonite. The age of the monzonite porphyry is unknown but by analogy with the Globe-Ray region to the north it may be doubtfully classed as Mesozoic or early Tertiary.

Many small fine-grained dikes and irregular bodies of intruded diabase cut the quartz monzonite and monzonite porphyry and, like the older rocks, are mineralized.

A large area of basalt flows, flow breccia, and agglomerate is present north and northwest of Tiger. The volcanic rocks appear to lie below the main beds of the Gila (?) conglomerate, suggesting a possible correlation with the dacite of the Globe-Superior area.

Dikes and irregular masses of rhyolite are found over a wide area in the San Manuel and Mammoth districts. These intrusive rocks cut all formations older than the Gila (?) conglomerate, and in lower Tucson Wash one is clearly truncated by the conglomerate. The rhyolite is partly replaced by ore in the St. Anthony mine, but in the San Manuel deposit it is clearly postore. A rhyolite breccia is closely associated with the intruded rhyolite at places.

Beds tentatively correlated with the Gila conglomerate are widely distributed throughout the San Manuel and adjacent areas. Locally the conglomerate is composed largely of very poorly sorted angular granite fragments. Its total thickness is unknown, but 1,395 feet was penetrated in one drill hole, and the formation may be several thousands of feet thick.

Alluvial slope deposits lie unconformably on the tilted and eroded Gila (?) conglomerate, and the bottoms of dry washes are filled with unconsolidated sand and gravel that belong to the Recent epoch.

The quartz monzonite and monzonite porphyry are so complexly and intimately related that their structure cannot be discerned from drill-hole data, but in general the porphyry lies above the main mass of the quartz monzonite, particularly in the eastern part of the area drilled. The structure of the dikes and irregularly intruded diabase and rhyolite also is not clear.

The Gila (?) conglomerate was extensively tilted and deformed. The prevailing strike of this formation is roughly northwest and the dip 25° to 45° NE., although in areas nearby dips of 60° have been recorded.

Many faults cut the conglomerate and underlying rocks. The mapped faults, however, probably represent only a small number of the existing ones, for gouge zones are fairly common in drill holes, and abrupt differences in the altitude of the top of the sulfide zone from hole to hole suggest the presence of faults, some of considerable displacement. The most reliable marker over much of the area for determining the location and offsets of faults is the bottom of the conglomerate. There is some evidence that the Mammoth fault extends into the San Manuel area from the St. Anthony mine where it is well known. An important fault, herein named the San Manuel fault, occurs along the southwest side of the exposed mineralized area and is clearly exposed in exploration pits, where it dips 32° SW. To the west the fault flattens somewhat. Another fault, known as the West fault, forms the east boundary of the exposed copper-bearing area. Where cut in a shaft near hole 9 the fault dips 60° E. This fault is believed to offset the eastward extension of the San Manuel fault.

East of the Mammoth fault and nearly parallel to it is the Cholla fault, a break that displaces alluvial slope gravels in Sar Pedro Valley. Drill logs indicate that the fault has a vertical displacement of 800 feet, with the east side downthrown.

Most of the rocks in the area that are of pre-Gila (?) age have been altered to a marked extent by hydrothermal solutions. Four closely related types of alteration have been distinguished, which are easily recognized on the surface by the color of the outcrops. The boundaries between alteration types are gradational and can be located only approximately. The alteration types are conveniently designated by their characteristic minerals: 1. kaolinite-alunite type, 2. hydromica-pyrite type, 3.

sericite-pyrite-chalcopyrite type, 4. marginal biotite type. Type 1 is very light gray, 2 is moderate red, 3 is reddish brown, and 4 is dark gray.

The most intensely altered rock in the region is the monzonite porphyry that forms an oval area about 700 by 800 feet just east of Red Hill. The altered rock consists mainly of kaolinite and alunite.

Altered rock of the hydromica-pyrite type crops out around the gray area of type 1. The red of these rocks is due to the oxidation of pyrite that extends to a depth of several hundred feet. The pyritic rock forms the footwall (north side) of the ore body, at least at places where the drill holes have passed through the better grade ore.

Type 3 alteration is coincident with the area of important copper mineralization. At the surface, the mineralized rock is reddish brown and has chrysocolla on the fracture surfaces. At depth the rock is essentially a sericite-pyrite-chalcopyrite aggregate with minor amounts of many other minerals, especially quartz, chlorite, kaolinite, hydromuscovite, leucoxene, and rutile.

Type 4 is a marginal, less intense type of alteration that occurs to the south of the ore body and peripherally to zone 3. This rock commonly appears relatively fresh in hand specimen, but in thin section the groundmass is found to consist of the alteration products—biotite, hydrobiotite, epidote, zoisite, and chlorite, and lesser amounts of many other minerals.

The ore body is composed of chalcopyrite and pyrite disseminated through quartz monzonite, monzonite porphyry, and diabase. Although the ore body has not been completely delimited by drilling, the copper content appears to fade out above and below except where the ore body crops out at the surface or is in contact with the conglomerate. Thus an arbitrary cut-off value of 0.5 percent copper was adopted by the San Manuel Copper Corporation to define the ore body.

The known length of the San Manuel ore body is 6,800 feet. The greatest width is unknown but in the eastern area the ore was found to have a maximum width of more than 3,000 feet.

There is no consistent difference in grade among ore in quartz monzonite, monzonite porphyry, and diabase. The copper content of the rhyolite, however, is always small, and it is believed to be derived largely from contamination in drilling.

Supergene oxidation and enrichment of the deposit have been extensive. Weathering processes have affected all the rocks in the area and have developed characteristic colors on surface exposures of the four types of altered rocks. At present the water table ranges from altitudes of 2,450 to 2,992 feet above sea level, corresponding to depths of 300 to 800 feet beneath the surface but these levels are being disturbed by drainage of shafts and other openings. The depth of oxidation ranges from 285 feet to 1,630 feet over a wide area. At least part of this range is a result of tilting of the region during structural disturbances.

Chrysocolla is the predominant copper mineral in the oxidized zone of the copper-bearing rock, but residual sulfides also are present. The copper probably has been diminished and redistributed to some degree by leaching. The average copper content in the oxidized zone is about three-fourths of 1 percent.

An irregular supergene sulfide zone is present below the oxidized ore. Downward percolating solutions have deposited chalcocite and other secondary copper sulfides as replacements of primary pyrite and chalcopyrite. The chalcocite ore probably averages about 1 percent copper and typically contains minor amounts of covellite, bornite, and native copper, and more or less residual pyrite and chalcopyrite. The zone of enrichment is not everywhere a single, simple zone, for oxidized areas occur within it, and, locally, secondary minerals occur with primary sulfides

in patches above and below. Lean extensions of the secondary ore occur beyond the limits of the primary ore shoot.

The zones of oxidation and enrichment are not related to the present erosion surface and water table and it is, therefore, concluded that they were developed during an earlier cycle of erosion.

The geologic age of the hypogene mineralization is unknown but, by analogy with other Arizona districts, is assumed as early Tertiary.

The estimate of reserves published by the San Manuel Copper Corporation in 1949 is 462,784,500 tons; of this total, 339,284,920 tons is classified as sulfide ore having an average copper content of 0.789 percent. Oxidized ore totals 123,499,580 tons, averaging 0.767 percent copper.

INTRODUCTION

LOCATION, CULTURE, ACCESSIBILITY

The San Manuel area is just south of the mining town of Tiger, Ariz., and the St. Anthony Mine, which is a widely known producer of gold, molybdenum, vanadium, lead, and zinc (fig. 1). The San Manuel area is in the Old Hat mining district of Pinal County at latitude approximately 110°42' W. and longitude 32°42' N. The area is 35 miles northeast of Tucson and is most easily reached by U. S. Highway 80 from Tucson to Oracle Junction, thence by State Highway 77 which passes through the San Manuel property between Oracle and Mammoth (fig. 2). State Highway 77 continues to a junction with U. S. Highway 70 east of Globe, making the area also accessible from the north. The area is shown on the Winkelman 30-minute quadrangle reprinted in 1932 and also on the new Mammoth 7½-minute quadrangle issued by the U. S. Geological Survey. The ore deposit is in secs. 34 and 35, T. 85, R. 16 E. of the Gila and Salt River meridian.

The nearest railroad is at Winkelman on the Gila River, 20 miles north of San Manuel and Tiger (fig. 1). Electric power and natural gas are available. About 2 cfs of water suitable for domestic and industrial use is available from the St. Anthony mine, and wells in the alluvial slope deposits of the San Pedro valley can be expected to furnish additional supplies. A considerable amount of water is pumped from the shafts sunk in 1951.

PHYSICAL FEATURES

The San Manuel deposit is in the "Sonoran Desert" section of the Basin and Range province and on a pediment that is a northward projection of the Santa Catalina Mountains (fig. 2). The pediment merges into the alluvial slope deposits of the San Pedro River Valley.

The topographic sheet shows the diagrammatic nature of the alluvial slopes on both sides of the San Pedro River. The surface is cut by a network of minor gullies that are a natural result of torrential rainfall on the relatively barren rocks of the desert. The copper

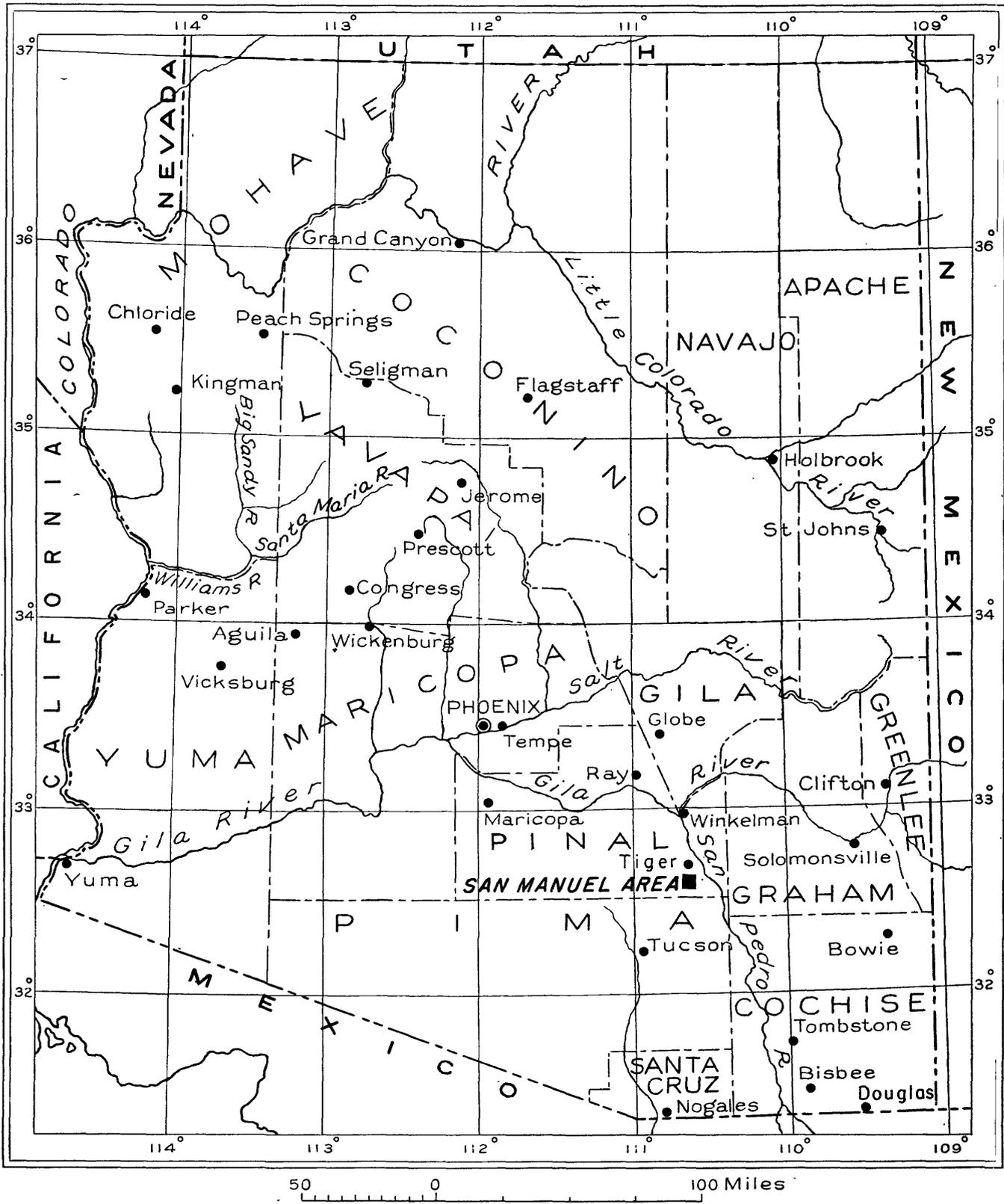


FIGURE 1.—Index map of Arizona showing the location of the San Manuel district.

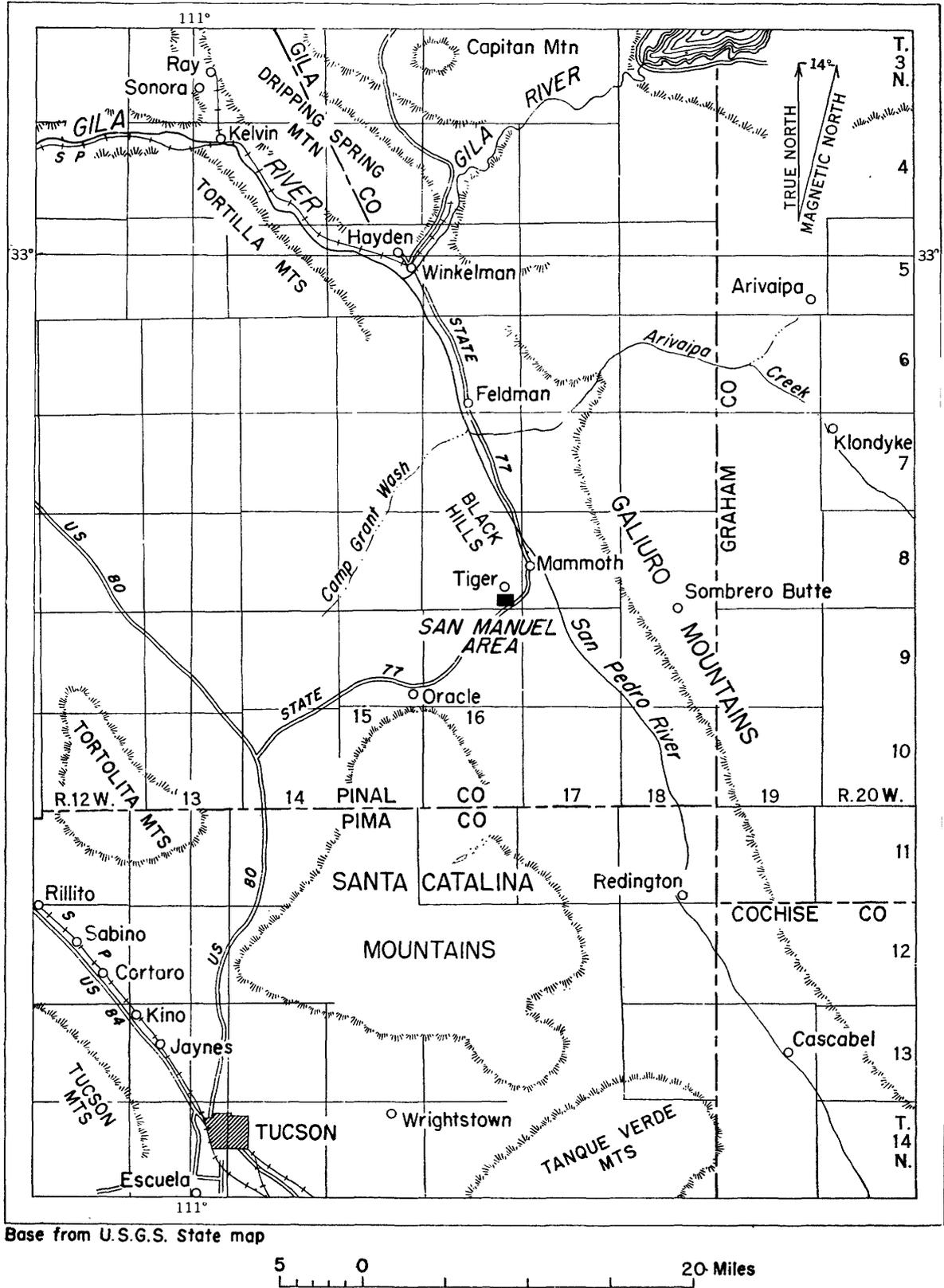


FIGURE 2.—Sketch map showing principal towns and topographic features in the area surrounding the San Manuel district, Arizona.

deposit is east of the deeply entrenched gorge of Tucson Wash that cuts through the San Manuel property.

The San Manuel area drains into the San Pedro River, which in turn flows into the Gila River at Winkelman 20 miles to the north. All the streams, including the San Pedro River, are intermittent and, with the exception of the river, seldom flow for more than a few hours following a rainfall.

CLIMATE AND VEGETATION

The climate of the San Manuel area is typical of southern Arizona and of the Sonoran Desert. The temperature rarely falls below freezing and for several months in summer temperatures as high as 100° F. are common and the average temperature is high. Because of the altitude, however, the extremely high temperatures characteristic of some of the lower parts of Arizona are not reached. The mean annual surface temperature is about 71.7° F., according to a projection of subsurface temperatures measured in several drill holes by Lovering (1948, p. 4) in December 1944.

Rainfall is low, and judging from adjacent areas, it is probably between 10 and 12 inches a year. The periods of greatest rainfall are in January and February and again in July and August when sudden and rather violent local thunderstorms are common. The water table is at considerable depth because of the slight replenishment.

Cacti of many kinds, but especially the giant saguaro and the cholla, are characteristic of the area. Greasewood, or creosote brush, is the common shrub, and mesquite and paloverde grow in the washes and other places of somewhat higher soil moisture. *Yucca* of various kinds is common, as is the ocotillo. Catsclaw is abundant in Tucson Wash. During periods of greater rainfall grasses spring up with astonishing vitality, and many kinds of desert flowers suddenly appear in bloom.

FIELD WORK AND ACKNOWLEDGMENTS

A preliminary study of the San Manuel copper deposit was made in March 1943 by B. S. Butler and N. P. Peterson of the U. S. Geological Survey. In the following October T. L. Chapman of the U. S. Bureau of Mines prepared a report on the same area. As a result of this preliminary work, the Bureau of Mines drilled four exploratory holes in November 1943 (Project 1466) and the Geological Survey assigned D. H. Kupfer to do the geologic work. He and G. L. Quick made a plane-table map of most of the area. The Bureau of Mines program of drilling was under the direction of J. H. Hedges, district engineer, and T. L. Chapman, project engineer. The Bureau's staff generously assisted in the geologic work.

The writer was assigned to the project in July 1944 and spent full time in the field until December of the same year. He did additional field work in March 1945, during the summers of 1945 and 1946, and on later visits to the area. Laboratory studies were made during the entire drilling program from November 1943 to February 1948. The writer used laboratory facilities at the University of Arizona in 1944 and at the University of Minnesota throughout the work. E. D. Wilson of the Arizona Bureau of Mines was especially helpful; J. W. Gruner and Lynn Gardiner of the University of Minnesota made many X-ray determinations of minerals, and F. F. Grout of the same university advised on petrological problems.

By permission of Tom Lyon of the International Smelting and Refining Company, Salt Lake City, E. F. Reed and D. N. Gill of the Houghton Group supplied data about drilling on claims east of San Manuel.

The major credit for the unusually full drilling information furnished by the San Manuel Copper Corporation is due A. J. McNab, Philip Kraft, Wesley P. Goss, G. R. Rubly, H. T. Ashby, and H. J. Steele, geologist for the corporation and the Magma Copper Company. It was Mr. Steele's generous cooperation throughout his company's program of drilling that made much of this report possible.

DESCRIPTIVE GEOLOGY

The rocks of the San Manuel area range in age from pre-Cambrian to Recent (pl. 1). Except for the conglomerates and other alluvial deposits of Tertiary and Quaternary age, the rocks are all igneous and the age of most of them can be identified only in a general way by correlation with rocks of surrounding areas.

The quartz monzonite (Oracle granite) of the area is of pre-Cambrian age, according to Peterson (1938a, p. 8). If this district is analogous to the Ray and other districts to the north, the monzonite porphyry that intrudes the quartz monzonite is probably of Mesozoic or early Tertiary age. Diabase intrudes the quartz monzonite and monzonite porphyry. In the Ray district similar diabase is assigned an early Mesozoic or late Paleozoic age (Ransome, 1919, p. 56).

A series of volcanic rocks crops out in a large area northwest of Tiger, and flows and tuffs are interbedded with the Gila(?) conglomerate of the San Manuel area (fig. 3). The age and relations of this series of volcanic rocks have not been completely determined but the latest flows clearly occur near the base of the Gila(?) conglomerate. The volcanic rocks in the large area northwest of Tiger appear to be earlier than the Gila(?) but probably are not earlier than Tertiary, although a Mesozoic age cannot be excluded.

The thick conglomerate, which is the most widespread

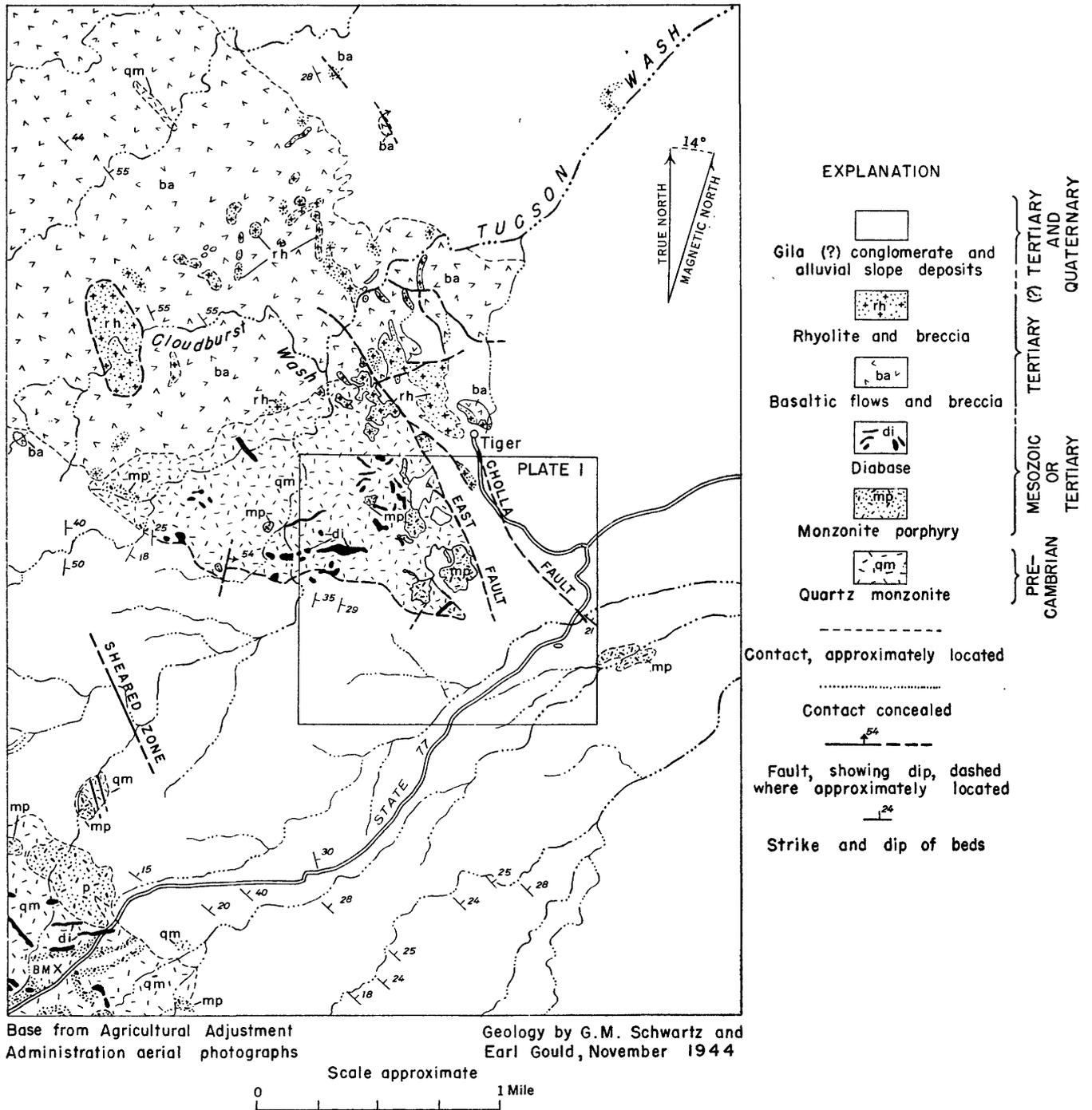


FIGURE 3.—Geologic map of area around San Manuel and Tiger, Ariz.

rock at the surface in the area, has been correlated with the Gila conglomerate in the Ray quadrangle to the north. It is overlain unconformably by the alluvial slope deposits of the San Pedro Valley. Recent alluvium and talus are abundant and in places lie above all the other rocks.

QUARTZ MONZONITE (ORACLE GRANITE)

DISTRIBUTION AND GENERAL RELATIONS

The quartz monzonite of the Mammoth mining camp area was correlated with the Oracle granite by Peterson (1938a, p. 8). The town of Oracle is 7 miles southwest of the San Manuel deposit and 8 miles from the St. Anthony mine at Tiger. Exposures of quartz monzonite occur sporadically from the San Manuel deposit to Oracle. The quartz monzonite is intruded by monzonite porphyry, diabase, and rhyolite and is overlain unconformably by Gila(?) conglomerate. North and northwest of Tiger basaltic lava flows overlie the older igneous rocks (fig. 3). Within the San Manuel area shown on the map the quartz monzonite forms the greater part of the exposed rocks older than the Gila(?) conglomerate.

The quartz monzonite was penetrated in all but 3 of the churn-drill holes (pls. 10-17). In general it lies near the base of the Gila(?) conglomerate in the western part of the explored area and is found at somewhat lower depths eastward where there is an increasing thickness of monzonite porphyry between the conglomerate and quartz monzonite.

Conglomerate and alluvium cover the quartz monzonite for more than a mile southwest of the San Manuel deposit. The basement rocks appear also at the southwest corner of the mapped area (fig. 3) where the quartz monzonite is intruded by the monzonite porphyry and by a few small diabase dikes. In these exposures and along State Highway 77 to Oracle an aplitic facies is unusually abundant.

PETROGRAPHY

Most of the quartz monzonite exposed at the surface or penetrated by the drill holes in the San Manuel area is highly altered. Hydrothermal alteration has been strong and pervasive, and weathering of the rock to depths of several hundred feet has further masked its original character. Relatively unaltered rock is exposed in cuts on State Highway 77, and very fresh large boulders are abundant on the slopes near Tucson Wash immediately southwest of the explored area.

The quartz monzonite is a pink, coarse-grained porphyritic rock liberally specked with dark-green to black biotite crystals ranging from 2 to 5 millimeters in diameter. Large subhedral feldspar grains as much

as 3 centimeters in length give the rock its porphyritic character. Mineralogically the rock is intermediate between biotite granite and quartz monzonite, but the silica and lime content shown by analysis confirms its classification as quartz monzonite.

Feldspar, quartz, and biotite are the essential minerals. Accessory minerals are muscovite, zircon, apatite, and magnetite. The freshest specimens show some secondary chlorite, sericite, hydromica, epidote, zoisite, and limonite. Within the altered area in and around the ore body the rock has been largely converted to secondary minerals.

The feldspars include microperthite, microcline, untwinned orthoclase, and oligoclase. The plagioclase varies in refractive index, is zoned, and gives extinction angles as great as or a little greater than the maximum for oligoclase. The interior of the grains has been replaced by hydromica and sericite to a greater extent than the outer zone. Probably the average plagioclase is oligoclase as reported by Peterson (1938a, p. 8).

A small amount of myrmekite is present among feldspar grains. Biotite constitutes from 5 to 10 percent by weight of the fresh rock, but it largely disappears in the early stage of alteration.

The accessory minerals of the quartz monzonite were studied by Raymond Rantala, who generally found that rutile, presumed to be mainly secondary from the breakdown of biotite, was as abundant as all other accessory minerals combined. Apatite and zircon are the only other minerals to appear consistently in heavy concentrates. The zircon crystals are of simple form, brown to hyacinth, and smaller in size but more abundant than the apatite crystals.

Chemical composition of slightly altered quartz monzonite from hole 67

[Analyst: Charlotte M. Warsaw]

| | | | |
|--------------------------------------|-------|-------------------------------------|-------|
| SiO ₂ ----- | 63.06 | TiO ₂ ----- | .96 |
| Al ₂ O ₃ ----- | 14.44 | P ₂ O ₅ ----- | .32 |
| Fe ₂ O ₃ ----- | 6.57 | CO ₂ ----- | None |
| CaO----- | 1.49 | SO ₃ ----- | .65 |
| MgO----- | 1.41 | FeS ₂ ----- | 2.88 |
| K ₂ O----- | 3.59 | MnO----- | .04 |
| Na ₂ O----- | 2.09 | CuO----- | .034 |
| H ₂ O+----- | 1.83 | | |
| H ₂ O----- | .30 | | 99.66 |

Total sulfur: 1.8 percent. Sp gr: powder...2.78; sp gr: bulk...2.67

The iron sulfide content shows that the analyzed rock was altered, but the relatively fresh appearance of the rock and normal amounts of oxides indicate that no great change in composition was produced by alteration.

Many partial chemical analyses of composite samples of quartz monzonite obtained from churn-drill cuttings were made by the Bureau of Mines. Most of the

analyzed samples are from the ore zones and to a lesser extent from the underlying pyritic zone. The average SiO_2 content of 69 samples of altered quartz monzonite is 68.91 percent, almost 6 percent higher than in the foregoing analysis. Average Al_2O_3 content of 64 analyses is 12.48 percent, nearly 2 percent lower than in the complete analysis.

APLITE FACIES

An aplite facies of the quartz monzonite is well developed in the exposures southeast of San Manuel along State Highway 77. In some of the outcrops aplite makes up nearly 50 percent of the rock. A few small aplite masses were observed in the vicinity of the ore deposit, especially on the south slope of Red Hill. The aplite is pale orange, pink, or light brown, and has a fine granitoid texture. In the churn-drill cuttings it was difficult to differentiate quartz monzonite and aplite, mainly because the aplite broke up into very small fragments having no very distinctive characteristics. Some of the cuttings were sufficiently coarse to permit identification of the altered aplite, but it is probably not abundant in the ore body.

A thin section of a specimen of aplite collected near State Highway 77, about 2 miles southwest of San Manuel, consists of a fine granitoid intergrowth of quartz and feldspar in a ratio of about 4 to 6. The grains average about a millimeter in diameter, with the largest about 2 millimeters. The feldspar consists of microcline and a sodic oligoclase, the latter being somewhat more abundant. There is a little interstitial myrmekite; and a small amount of biotite and muscovite, not more than 2 percent, is distributed throughout. Small leucoxene and iron oxide grains probably were derived from alteration of original magnetite-ilmenite.

BIOTITE SCHIST XENOLITHS

A few inclusions of biotite schist were noted in some of the drill cuttings of quartz monzonite. The largest inclusion was in hole 6 from 390 to 405 feet, and another occurred from 745 to 755 feet. This 10-foot zone averaged 2.07 percent copper, about double the amount in the quartz monzonite on either side, thus indicating that the biotite schist was a favorable host for the ore-bearing sulfides. Other inclusions of biotite schist were observed in the cuttings, but most of these apparently were small and made up only a part of the cuttings from a 5-foot run. The most conspicuous were in hole G from 1,705 to 1,715 feet, in hole K from 1,100 to 1,105 and 1,140 to 1,145 feet, and in hole 45 from 2,105 to 2,120 feet. All these examples had about average copper content.

AGE

The age of the quartz monzonite cannot be determined in the San Manuel area, but, as noted by Peterson (1938a, p. 8), the Oracle granite is overlain at Camp Grant Wash, 10 miles north of Tiger, by the Apache "series" of pre-Cambrian age. About the same distance to the south near Oracle the Apache group overlies the Oracle granite (the quartz monzonite of this report). There the Apache is overlain by the fossiliferous Upper Cambrian Abrigo limestone. Because of the similar lithology and the nearly continuous exposures of quartz monzonite from Oracle to San Manuel, the altered quartz monzonite of the ore deposit is undoubtedly part of the Oracle granite batholith and of pre-Cambrian age.

MONZONITE PORPHYRY

The monzonite porphyry is an important rock in the ore deposit, and was described as andesite porphyry by Peterson (1938b, p. 9). The rock is actually a quartz monzonite porphyry but the quartz occurs only in the groundmass, and to avoid confusion with the unit mapped as quartz monzonite (Oracle granite), the rock is termed monzonite porphyry.

DISTRIBUTION AND GENERAL RELATIONS

The distribution of the monzonite porphyry is imperfectly known because a blanket of Gila(?) conglomerate and later alluvial deposit covers much of the area. The porphyry has been observed at places over a fairly wide area surrounding the San Manuel deposit, and there are exposures extending southwest beyond the 9-square-mile area where reconnaissance mapping was done (fig. 3).

Within the area of outcrop of rocks older than the Gila(?) conglomerate, the porphyry has intruded the quartz monzonite in an extremely irregular fashion (pls. 10-17). In the outcrop area of the ore body, bounded by the San Manuel and West faults, the monzonite porphyry is the principal rock but contains irregular inclusions of quartz monzonite. A later diabase dike and an intrusive rhyolite cut the porphyry. The southeast slope of Red Hill is mostly porphyry but is partly obscured by talus and wash. The area between Red Hill and the Mammoth fault is underlain by very highly altered porphyry, and a considerable area of porphyry also exists on the south slope of the hill between Red Hill and Tiger. Small dikes and irregular intruded masses occur throughout the quartz monzonite area. Small masses of porphyry also occur in Tucson Wash directly west of Red Hill and also farther west along a tributary of Tucson Wash.

Exposures of the porphyry are abundant in the area of outcrop of older rocks along State Highway 77, about 2 miles south of San Manuel (fig. 3). There a series of dikelike and other very irregular masses of porphyry occurs in quartz monzonite and extends westward an unknown distance beyond the area examined. Peterson (1938a, pl. 1) shows only one small body of porphyry on the map of the Mammoth district, but others were discovered along the south margin of his map area. None was observed north of Tiger, but the porphyry may be beneath later volcanic rocks and Gila(?) conglomerate.

Drill cuttings from 105 churn-drill holes, totaling 198,531 feet, showed that only one hole (no. 54) did not cut monzonite porphyry. The monzonite porphyry is most abundant in the eastern part of the deposit where it forms a large, probably tabular body underlying the unconformable Gila(?) conglomerate (pls. 10-17). Farther west in the explored area there is no such large body but the monzonite porphyry intrudes the quartz monzonite in a very complex manner, as suggested by the following log:

Log of hole 68; drill grid coordinates: 1299.2 S., 1000.0 W.

| Depth (feet) | Thick-ness (feet) | Formation | Description |
|--------------|-------------------|--|--|
| 0-800 | 800 | Gila(?) conglomerate | Typical biotite type, light alteration; some sulfide below 800 ft. |
| 800-1,485 | 685 | Monzonite porphyry | |
| 1,485-1,555 | 70 | Rhyolite | |
| 1,555-1,565 | 10 | Quartz monzonite | |
| 1,565-1,585 | 20 | Rhyolite | |
| 1,585-1,595 | 10 | Monzonite porphyry | |
| 1,595-1,620 | 25 | Monzonite porphyry and quartz monzonite. | |
| 1,620-1,625 | 5 | Monzonite porphyry and diabase. | |
| 1,625-1,630 | 5 | Diabase | |
| 1,630-1,720 | 90 | Monzonite porphyry | |
| 1,720-1,725 | 5 | Monzonite porphyry and quartz monzonite. | |
| 1,725-1,780 | 55 | Quartz monzonite | More pyrite and chalcopyrite below 2,000 ft. |
| 1,780-1,790 | 10 | Monzonite porphyry and quartz monzonite. | |
| 1,790-1,850 | 60 | Quartz monzonite | |
| 1,850-1,880 | 30 | Quartz monzonite and monzonite porphyry. | |
| 1,880-1,895 | 15 | Quartz monzonite | |
| 1,895-1,910 | 15 | Quartz monzonite and monzonite porphyry. | |
| 1,910-1,985 | 75 | Quartz monzonite | |
| 1,985-2,005 | 20 | Quartz monzonite and monzonite porphyry. | |
| 2,005-2,115 | 110 | Quartz monzonite | |

Log of hole 68; drill grid coordinates: 1299.2 S., 1000.0 W.—Con.

| Depth (feet) | Thick-ness (feet) | Formation | Description |
|--------------|-------------------|--|--|
| 2,115-2,130 | 15 | Quartz monzonite and diabase. | Porphyry is very dark, fine-grained. |
| 2,130-2,155 | 25 | Quartz monzonite | |
| 2,155-2,160 | 5 | Quartz monzonite and monzonite porphyry. | |
| 2,160-2,170 | 10 | Monzonite porphyry | |
| 2,170-2,180 | 10 | Monzonite porphyry and quartz monzonite. | |
| 2,180-2,235 | 55 | Quartz monzonite | More disseminated pyrite and chalcopyrite from 2,230 ft. to bottom than above. |
| 2,235-2,240 | 5 | Quartz monzonite and monzonite porphyry. | |
| 2,240-2,245 | 5 | Monzonite porphyry | |
| 2,245-2,295 | 50 | Quartz monzonite | |
| 2,295-2,310 | 15 | Quartz monzonite and monzonite porphyry. | |
| 2,310-2,355 | 45 | Quartz monzonite | |
| 2,355-2,370 | 15 | Quartz monzonite and monzonite porphyry. | |
| 2,370-2,400 | 30 | Quartz monzonite | |
| 2,400-2,430 | 30 | Quartz monzonite and monzonite porphyry. | |
| 2,430-2,445 | 15 | Monzonite porphyry | |
| 2,445-2,460 | 15 | Quartz monzonite | Shear zone 2,560 ft. to bottom. Hole had been reduced to 4 in. and no further progress was possible. |
| 2,460-2,475 | 15 | Monzonite porphyry and quartz monzonite. | |
| 2,475-2,575 | 100 | Quartz monzonite | |

Hole 106 at 1700 S., 2085 W. on the drill grid, somewhat southeast of the other holes, penetrated a great thickness of monzonite porphyry beneath the conglomerate; this suggests a large monzonite porphyry body south of the smaller masses.

It is not possible to determine the major structure of the monzonite porphyry, for much of the porphyry is hidden beneath younger rocks. A central stock may be present somewhere in the region, and the known bodies may be irregular offshoots of it. The principal mass of monzonite porphyry in the explored area lies above quartz monzonite; so, the porphyry may be an intruded sheetlike mass (pl. 14). The small size of grain indicates a mass of moderate size but not a batholith or even a large stock. The grains resemble those of some of the intrusive bodies mapped by Ransome (1919, pl. 2) in the Globe-Ray region not far to the north.

PETROGRAPHY

Completely unaltered monzonite porphyry has not been found associated with the ore body, and least altered specimens have come from an area about 2 miles southwest. This least altered monzonite porphyry is medium light gray, and is highly porphyritic, with phenocrysts of feldspar as much as 1 centimeter in maximum length and small biotite phenocrysts usually not more than 3 millimeters in diameter (pl. 3A, B). The normally light gray feldspars give the rock a spotted appearance.

The essential minerals are feldspar, quartz, and biotite. The feldspar phenocrysts are plagioclase; the fine-grained groundmass is a mosaic of quartz and orthoclase. The plagioclase is highly altered but identifiable grains proved to be andesine-oligoclase ($Ab_{70}An_{30}$).

Megascopically the rock is a monzonite porphyry, but the abundance of quartz in the very fine-grained groundmass warrants a microscopic classification of quartz monzonite porphyry.

The accessory minerals are rutile, apatite, magnetite, and zircon. Rutile is abundant (pl. 2F). In contrast to the constituents of the quartz monzonite, apatite is more abundant in monzonite porphyry than zircon, and its zircon is in colorless, doubly terminated crystals.

Common alteration products include: sericite, chlorite, epidote, hydromica, hydrobiotite, potash clay, kaolinite, alunite, rutile, leucoxene, and pyrite. Several other secondary minerals occur less commonly.

The exact chemical composition of the unaltered porphyry is unknown. However, the composition may be approximated from available data on the least altered facies, shown by a complete analysis of a composite sample from hole H (pl. 9I). There are three holes: H, H1, and H2, which are within a few feet of one another. Holes H and H1 were abandoned because of difficulties in drilling and did not reach the necessary depth. Hole H is in the hanging wall of the ore body, and the rock is only slightly altered.

Chemical composition of composite sample of monzonite porphyry from hole H at 825 to 875 feet

[Analysist: Charlotte M. Warshaw]

| | | | |
|--------------------------------------|-------|-------------------------------------|-------|
| SiO ₂ ----- | 64.88 | TiO ₂ ----- | .56 |
| Al ₂ O ₃ ----- | 15.01 | MnO----- | .04 |
| Fe ₂ O ₃ ----- | 1.06 | CuO----- | .19 |
| FeO----- | 2.42 | P ₂ O ₅ ----- | .19 |
| CaO----- | 2.59 | CO ₂ ----- | 1.35 |
| MgO----- | 1.44 | SO ₃ ----- | 1.04 |
| K ₂ O----- | 3.14 | S----- | None |
| Na ₂ O----- | 3.02 | | |
| H ₂ O+----- | 2.03 | | 99.33 |
| H ₂ O----- | .37 | | |

Sp gr: powder . . . 2.66; sp gr: bulk . . . 2.59

Partial analyses of 43 composite samples of monzonite porphyry made by the Bureau of Mines show an average SiO₂ content of 64.14 percent, a very close correlation with that given above. Forty-two determinations of Al₂O₃ give an average of 15.21 percent, again a very close correspondence.

The amounts of CO₂ and SO₃ in the complete analysis indicate a moderate amount of alteration, possibly partly due to weathering.

AGE AND CORRELATION

The monzonite porphyry cuts rocks of pre-Cambrian age and is overlain by rocks of late Tertiary age. In the Ray and Miami areas, however, Ransome (1919, pl. 45, p. 123) shows that the Schulze granite and its related porphyry facies, the quartz monzonite and diorite porphyries at Ray, are probably Tertiary, but he also states that they are probably pre-Tertiary. They are definitely post-Carboniferous. The monzonite porphyry is considered as probably Mesozoic or early Tertiary age in this report.

DIABASE

DISTRIBUTION AND GENERAL RELATIONS

Dikes and irregular intruded masses of diabase are exposed throughout the part of the San Manuel area not covered by Gila(?) conglomerate or alluvium (pl. 1). Small dikes were also observed in the area of outcrop of quartz monzonite and monzonite porphyry 2 miles southeast of the San Manuel deposit.

Diabase was cut in 28 of the 105 churn-drill holes on the San Manuel property. The drill hole numbers are as follows: 3, 11, 13, 16, E, F, J, K, N, O, R, 46, 47, 54, 56, 60, 67, 68, 69, 72, 73, 74, 76, 82, 84, 86, 90, and 102. It does not appear to have been cut in the Houghton Group drilling to the east. Study of the distribution of the diabase in the drill holes shows that it is widely distributed in the central and western parts of the deposit but is rare in the eastern part. Some holes penetrated several individual masses, most of which are small. The maximum thickness penetrated was 337 feet in hole 46 from 1,320 to 1,657 feet—the bottom of the hole. Two hundred feet to the south hole 47 penetrated more than 225 feet of diabase. This area along the 2,200 W. coordinate showed the largest amount of diabase in the drilling. Hole 76 penetrated 240 feet of diabase between 2,335 and 2,575 feet. A few other holes cut thickness ranging from 50 to 200 feet, but most bodies were less than 50 feet thick, often only 10 or 15 feet. In all the drill holes the true thickness is unknown, but it is probable that in some holes the diabase cut so that the thickness was greatly exaggerated.

A diabase dike marks a break in the main ore body along the north side of the outcrop area between holes

1 and 11 (pl. 1), and early geologists thought this dike had limited the ore body. At the surface there is a sharp distinction between the porphyry on the two sides of the narrow dike. South of the diabase dike the porphyry is reddish except for innumerable fractures coated by chrysocolla. North of the dike the rock is medium to dark red and contains no visible copper. At depth some ore occurs north of the dike, but this is mostly a result of supergene enrichment.

The diabase apparently acted as somewhat of a barrier to the movement of ore-bearing solutions although it is altered and metallized, as is well shown in outcrop and also in drill cuttings. Inspection of the assay graphs plotted against the drill-hole logs shows no consistent difference in the copper content of diabase and that of quartz monzonite and monzonite porphyry. Diabase in the typical ore zone from 6 holes averaged 0.76 percent copper for a total of 160 feet.

PETROGRAPHY

The diabase is dark gray to dark reddish gray, and usually contrasts with the lighter quartz monzonite and monzonite porphyry. In drill cuttings some unusually dark-gray porphyry much resembled the diabase and led to a little confusion in megascopic classification.

The diabase is very fine grained except in a few of the thicker masses. The texture has been obscured by alteration, and careful examination with a hand lens is often necessary in order to see the diabasic texture.

All the diabase exposed at the surface is considerably affected by weathering, and all drill cuttings obtained were hydrothermally altered and, in places, weathered. In thin section the diabasic texture usually is evident, though by no means clear cut, owing to alteration. Plagioclase grains are lath shaped but have been largely altered to sericite, hydromica, kaolinite, and allophane. Although precise determination of the plagioclase is impossible, the extinction angle is about 20°, indicating labradorite. Diabase at Ray contains calcic labradorite or bytownite (Ransome, 1919, p. 54).

The original ferromagnesian mineral, probably augite, is altered to chlorite, nontronite, biotite, antigorite, uralite, calcite, rutile, leucoxene, and limonite. The principal accessory minerals are magnetite and ilmenite and in some specimens biotite. Ilmenite has been altered to leucoxene which has also formed from titanium liberated by the destruction of the ferromagnesian minerals. Magnetite has been partly altered to hematite in some specimens. Much of the more altered diabase contains spherulites of chlorite.

AGE AND CORRELATION

The diabase is clearly younger than monzonite porphyry and quartz monzonite and is here considered of probable Mesozoic or Tertiary age (see pl. 1). It is

overlain unconformably by the Gila(?) conglomerate and is also cut by the rhyolite dikes. The diabase is heavily impregnated with pyrite in the pyritic zone and contains chalcopyrite in the hypogene ore zone. Accordingly, the diabase is undoubtedly preore in age. It is similar to diabase found in the Globe, Ray, and Miami districts which Ransome (1923, p. 11) concluded was either early Mesozoic or late Paleozoic. The present writer thinks that the diabase at San Manuel is of neither of these ages because in the Ray area the diabase is believed to be younger than the various porphyries that may have their counterpart in the monzonite porphyry. Therefore, the diabase at San Manuel may be younger than that at Ray, or conversely, the monzonite porphyry may be earlier than the porphyries at Ray. Mapping of the area between Ray and San Manuel should clarify many of these obscure points.

ANDESITE PORPHYRY

In the ore on the dump of shaft 2 a few lumps of a dark, apparently unweathered porphyry were collected in March 1950. H. J. Steele said of it:

This dark porphyry occurred as a 2-ft.-thick horizontal band of apparent small lateral extent. It pinched out, or nearly pinched out, within the area of the shaft. It was found between the 210th and 211th set, or at 1,050 to 1,055 ft. below the collar. I remember a very similar dark porphyry being intersected in one or more holes in this area, but it did not seem extensive nor of great significance as far as ore was concerned.

The porphyry is dark gray, with numerous phenocrysts of feldspar and biotite. A thin section shows that andesine, hornblende, and biotite phenocrysts occur in a very finegrained groundmass that consists mainly of minute needlelike grains of oligoclase with finely disseminated magnetite. Some of the feldspar phenocrysts are fragments of crystals and two small lens-shaped inclusions of monzonite porphyry are also present. One hand specimen contains a granite fragment about 1 inch across. Calcite fills minute fractures in the rock.

Composition of andesite porphyry from shaft 2 at 1,050 to 1,055 feet

[Analyst: Eileen Oslund.]

| | | | |
|--------------------------------------|--------|-------------------------------------|--------|
| SiO ₂ ----- | 59. 10 | P ₂ O ₅ ----- | 0. 30 |
| Al ₂ O ₃ ----- | 17. 05 | S----- | Tr. |
| Fe ₂ O ₃ ----- | 2. 69 | MnO----- | 0. 04 |
| FeO----- | 3. 48 | BaO----- | 0. 07 |
| MgO----- | 2. 79 | | |
| CaO----- | 4. 29 | | 99. 96 |
| Na ₂ O----- | 4. 34 | | |
| K ₂ O----- | 2. 09 | | |
| H ₂ O+----- | 1. 47 | Norm | |
| H ₂ O----- | 0. 33 | Q----- | 14. 70 |
| CO ₂ ----- | 1. 02 | Or----- | 12. 23 |
| TiO ₂ ----- | 0. 90 | Ab----- | 36. 68 |
| | | An----- | 13. 34 |

Composition of andesite porphyry from shaft 2
at 1,050 to 1,055 feet—Continued

| Norm—Continued | | Norm—Continued | |
|--------------------|-------|------------------|-------|
| Hy..... | 9.90 | Cc..... | 2.30 |
| M+..... | 3.94 | C..... | 2.86 |
| Il..... | 1.67 | | |
| Ap..... | 0.67 | | 98.29 |
| Sp gr: powder..... | 2.730 | Sp gr: bulk..... | 2.705 |

This rock closely resembles the Tertiary andesite lava flow that crops out near hole 71, and it is possible that it represents an intruded body of the andesitic lavas that lie below the Gila(?) conglomerate.

VOLCANIC ROCKS

Basaltic flows, flow breccia, and agglomerate form a large area north and northwest of Tiger (fig. 3). The flows lie on the quartz monzonite of pre-Cambrian age and local cover of conglomerate. Peterson (1938, p. 11) states that a minimum thickness of 3,600 feet is exposed. He gives many details about these associated volcanic rocks but expresses no opinion as to their age. Relations along the southeastern margin of the volcanic rocks show that they are younger than the quartz monzonite, monzonite porphyry, and diabase. The volcanic rocks are older than the Gila(?) conglomerate, as demonstrated in the Tucson Wash area, but patches of an older conglomerate lie between the flow and the quartz monzonite.

A lava flow crops out in the wash between hole 17¹ and State Highway 77 and good exposures of conglomerate occur on the north side of the wash and lie stratigraphically above the lava flow. The flow rock is reddish gray, and some parts have a poorly developed amygdaloidal structure. A thin section of this rock reveals a diabasic and slightly trachytic texture, and rudely lath-shaped feldspar grains make up a high percentage of the rock. The feldspar is relatively clear but has a patchy appearance under crossed nicols. The refractive index is lower than that of balsam; so the lath-shaped grains are probably albite. The patchy appearance suggests that the albite is secondary. Pyroxene has been largely altered, but a few grains remain. Magnetite has been largely altered to hematite, and dusty hematite disseminated throughout gives the rock its reddish color. Late carbonate veinlets and patches, which cut the other minerals, are moderately abundant. The general character of the rock suggests that it was primarily an andesite, although the feldspar is now alkalic. Drill holes show that this flow lies very close to, if not on, the eroded surface of the intruded rocks below and probably is an outlier of the older volcanic rocks previously described.

¹ All San Manuel drill holes are designated by simple numbers or letters with a subnumber when a hole was abandoned and begun again. All Houghton Group drill holes are preceded by the letter H. (See table 4.)

RHYOLITE

DISTRIBUTION AND GENERAL RELATIONS

Dikes and irregular intruded bodies of rhyolite are found over a wide area in the San Manuel and Mammoth districts. In the immediate vicinity of the San Manuel deposit two rhyolite bodies crop out. Two others were cut in shaft 2 and many were cut in the churn-drill holes. The largest exposed body of rhyolite and rhyolite breccia is about 800 feet southeast of the crest of Red Hill and just north of the principal outcrop of the ore deposit and extends from the San Manuel fault northward across a deep gully (pl. 1). The second exposure is east of Red Hill and north of the ore deposit. Four narrow outcrops appear to form part of a narrow dike which strikes about N. 48° E. The greatest thickness of rhyolite in the drill holes is 265 feet, in hole 51. Other thick zones were 145 feet in hole 7 and 105 feet in hole 69. The rhyolite is scattered throughout the ore body except in the east part where it was found only in hole 52 at the extreme north side of the drilled area.

Peterson (1938b, pl. 36) showed that dikes and irregular intruded masses of rhyolite are abundant in the vicinity of the St. Anthony mine, and field work by the present writer northward and westward from Tiger showed (fig. 3) that intruded rhyolite is abundant in a large area of basalt flows. Most of these masses are not dikes but are oval or irregularly elongate. The largest is well exposed where Cloudburst Wash cuts a steep meandering canyon through the middle of the body.

The rhyolite at the north side of the ore zone cuts through the diabase dike. Flow structure is characteristic of the rhyolite near its borders, and the breccia associated with this intruded rhyolite is composed mainly of rhyolite fragments, but also contains some fragments of quartz monzonite. The rhyolite is closely associated with copper-bearing rock, but, except for a thin zone of copper stain along the contact, the rhyolite is barren.

The rhyolite cut in the drill holes is barren, except for small amounts of a copper oxide mineral presumably deposited by supergene solutions. It is everywhere later than the ore and invariably the copper content drops abruptly where rhyolite is penetrated, as shown by the assay graphs (pls. 10, 12, and 17). The small copper content is doubtless due to contamination. Assays indicate that a rhyolite dike found in the midst of ore-bearing monzonite porphyry in shaft 2 is essentially barren.

The importance of rhyolite in the St. Anthony mine and adjacent areas has been described in some detail by Peterson (1938a, pp. 12-13, 17-18). Large masses of

breccia composed mainly of rhyolite fragments in a banded matrix are closely associated with the rhyolite.

PETROGRAPHY

The rhyolite is usually pink or creamy in outcrop because of a small amount of disseminated iron oxide derived from oxidation of pyrite. At depth the rock is light gray. It is very fine grained, generally with small oligoclase and microcline phenocrysts and a few quartz phenocrysts. The euhedral form of some of the quartz phenocrysts shows corrosion. The groundmass makes up the bulk of the rock and consists of alkalic feldspar with occasional small interstitial grains of quartz; most, if not all, the quartz was introduced. Thin sections are somewhat clouded with earthy red iron oxide and very minute inclusions having low index of refraction, believed to be allopahne. The rock lies just about on the border line between rhyolite and trachyte, for quartz probably does not exceed 5 percent of its content.

Thin sections show that the breccia contains fragments of basalt, rhyolite, quartz, and feldspar, with a very fine-grained rhyolitic matrix.

AGE

The rhyolite is the youngest of the igneous rocks in the district and is considered of probable Tertiary age. It cuts clearly across quartz monzonite, monzonite porphyry, and dike-like masses of diabase. It cuts vertically through basalt flows in the canyon of Cloudburst Wash and exhibits flow banding parallel to its margins.

The rhyolite is older than the Gila(?) conglomerate, as shown by a sedimentary contact exposed in Tucson Wash northeast of Tiger. The rhyolite probably projected above the surrounding surface so that the sedimentary contact now exists only at the south end of the smaller of two outcrops. It is also possible that the rhyolite owes its position to faulting, but this possibility is lessened by the fact that parallel faults in the Tiger and San Manuel areas have the downthrow on the east, whereas it would have to be on the west side to have brought the rhyolite to the altitude of the present surface.

At the time of the publication of the preliminary report (Schwartz, 1945) it was thought that decomposed rhyolite that was observed in a small outcrop cut conglomerate southeast of the site of shaft 1. Excavation in this area has shown that this exposure is, in fact, a tuff.

GILA (?) CONGLOMERATE

DISTRIBUTION AND TOPOGRAPHIC EXPRESSION

Gila(?) conglomerate is widely distributed both within the area of the San Manuel deposit and in the sur-

rounding region, although eastward it disappears beneath the alluvial slope deposits of the San Pedro River. The conglomerate and overlying alluvial deposits cover most of the eastern and southern parts of the area shown in figure 3. The conglomerate covers the greater part of the ore body. In general, the conglomerate was rather easily eroded and forms rounded slopes and ridges.

STRATIGRAPHY

At places the Gila(?) conglomerate rests unconformably on the older rocks, but in the vicinity of the ore body the contact is, at places, a fault. The pebbles and boulders range from angular to subangular to rounded and are poorly sorted and stratified. Beds are lenticular and can rarely be traced for more than a few tens of feet, with the exception of tuffs in the lower part which are more continuous. The formation is only moderately consolidated and weathers readily to a characteristic gray bouldery or gravelly soil.

The composition of the formation varies greatly, both horizontally and vertically. At places the formation is composed mainly of broken granite ranging from fine arkosic material to large boulders, and possibly represents remnants of an older conglomerate that to the northwest lies beneath the flows. In the area immediately over the San Manuel deposit, fragments of volcanic rocks in sandy clay make up the bulk of the conglomerate. In drill cuttings this material grades into rock that is composed almost entirely of volcanic fragments. Some difficulty was encountered, therefore, in classifying the rock from churn-drill cuttings. Conglomerate containing volcanic breccia, and fragments of lava flows furnish just about the same type of cuttings.

In most of the drilling no attempt was made to differentiate between the various types of material within the conglomerate, except in the Houghton Group drill holes east of the Bureau of Mines and the San Manuel Copper Corporation holes. In holes 9 and 10 of the Houghton Group project the following differentiation was made by the company geologists.

Log of hole H9; drill grid coordinates: 506.1 N., 395.9 E.

| | |
|---------------|--|
| Depth (feet): | |
| 0-10----- | Surface detritus. |
| 10-190---- | Mixed conglomerate--- Fragments of granite, quartz monzonite, andesite, rhyolite, basalt, and quartzite. |
| 190-510--- | Volcanic(?) conglomerate. |
| 510-740--- | Andesite, fine-grained flows. |
| 740-1,115.. | Mixed conglomerate. |

Log of hole H10; drill grid coordinates: 2322 S., 3606 E.

| Depth (feet): | |
|---------------|-------------------|
| 0-10 | Surface detritus. |
| 10-455 | Conglomerate. |
| 455-655 | Andesite flow. |
| 655-780 | Basalt flow. |
| 780-1,290 | Conglomerate. |

Thin beds of tuff occur interbedded in the conglomerate. Their distribution indicates that there are several beds at different horizons, but the number and distribution are not yet known. A good exposure was revealed when the site for hole 7 was graded and another exposure is about 500 feet south of shaft 1. The latter was originally thought to be weathered rhyolite, but grading in the area in 1948 revealed its fragmental character.

The tuffs are typically light gray and are specked with small biotite flakes. Near the contact with the conglomerate, small pebbles or fragments, mainly of volcanic rocks, are embedded in the tuff. A faint bedding may be seen in some parts. Thin sections show that the tuff is composed chiefly of volcanic glass, and a small amount of biotite, quartz, feldspar, and rock fragments. The glass is slightly devitrified but is still isotropic. These tuff beds should help considerably in the determination of the detailed stratigraphy and structure of the conglomerate.

THICKNESS

The total thickness of the Gila(?) conglomerate in the San Manuel area is unknown. It ranges from a knife edge to 1,208 feet at a place where the conglomerate is believed to be faulted against the underlying rocks. The Santa Maria Mining Co. drilled a hole near State Highway 77 east of Tiger reported to have penetrated 2,020 feet of alluvial slope deposits and Gila(?) conglomerate without reaching the base of the conglomerate. The average dip of the deposit is about 30° to the northeast and it exists over a wide area; so a thickness of several thousand feet is indicated. Ransome (1923, p. 14) estimates 8,000 feet of Gila conglomerate in the Ray quadrangle 25 miles to the north.

ORIGIN

The Gila(?) conglomerate was deposited during a period of active erosion and in a region of high relief. Volcanic activity doubtless played an important role both preceding and during the deposition of the Gila(?). An arid climate, not unlike that of the present time, is inferred because much of the fragmental material shows evidence of disintegration by desert weathering. The large blocks of granite that locally form a part of the conglomerate suggest high mountains and steep slopes. Flash floods under such conditions are capa-

ble of moving large volumes of material including unusually large boulders.

STRUCTURE

The detailed structure of the Gila(?) conglomerate is difficult to determine because of poor exposures. Throughout the immediate area of the San Manuel deposit the conglomerate dips on the average of 30° NE., but dips as high as 60° were observed in the area surrounding the deposit and are especially discernible north of Tiger. No dips of less than 15° were seen. Ransome (1919, p. 72) noted dips as high as 75° in the Ray quadrangle, and Bryan (1926, p. 169) stated that the Gila in the San Pedro Valley is deformed by minute faulting and crumpling where mountain blocks were pushed through the less competent Gila.

Data from outcrops and drill holes show clearly that the bedding of the conglomerate dips more steeply than the dip of the unconformity at the base of the conglomerate (pls. 15 and 16). In the eastern part of San Manuel Copper Corporation property good exposures of conglomerate along a dry wash near hole 72 show a dip of 20° to 30°, whereas the upper part of the unconformity in holes nearby dips only 10°.

The fact that the bedding of the conglomerate dips more than the unconformity underlying it may be explained by the higher initial dip of the conglomerate or by an upheaval that caused the conglomerate to overlap on a rising surface.

AGE AND CORRELATION

The name Gila conglomerate was proposed by Gilbert (1875, pp. 540-541) for a series of valley beds of which conglomerate formed a major part. The beds were examined by Gilbert along the upper Gila River and its tributaries in Arizona and New Mexico and the term has been used for similar deposits distributed over a wide area in Arizona. Large areas of Gila conglomerate were mapped by Lindgren in the Clifton-Morenci district and by Ransome in the Globe, Miami, and Ray districts. Lava flows are interbedded with the conglomerate in many localities. The deposits of conglomerate were evidently formed in valleys between high mountain ranges and, therefore, correlation of these deposits can be made from place to place only in a general way and does not imply that the deposits were continuous with the type area. Nevertheless, it is true that a description of the formation classified as Gila(?) conglomerate in the San Manuel area is very much like Gilbert's original description and, in more detail, like those of Lindgren and Ransome for other areas in eastern Arizona.

The age of the Gila conglomerate has usually been considered as Pliocene and Pleistocene, but it seems best for the present to designate the conglomerate in the

San Manuel area—because of its uncertain correlation with the Gila described by Gilbert—as the Gila(?) conglomerate and to consider it of Pliocene(?) and Pleistocene(?) age.

ALLUVIAL SLOPE DEPOSITS

The San Pedro River occupies a deep valley that extends from the Mexican border west of Bisbee, Ariz., to its junction with the Gila River at Winkelman about 20 miles north of the San Manuel copper deposit. The San Manuel deposit is about 3 miles west of the river where it flows between the Galiuro Mountains on the east and the Black Hills and Santa Catalina Mountains on the west. This area between the mountains is a broad trough probably formed by basin and range type of faulting, and then partly filled with detritus. The river has excavated its present valley in this detritus. The topography is well shown by the Winkelman 30-minute quadrangle and by the new Mammoth 7½-minute sheet. The San Pedro River is now bordered on each side by a remarkably uniform but dissected alluvial slope several miles wide. In the lower part of Tucson Wash, northeast of Tiger, the older Gila(?) conglomerate dips 25° NE.; alluvial slope gravels unconformably lie on the truncated older beds. These alluvial slope deposits dip a few degrees toward the San Pedro and were deposited by streams joining a master stream near the present course of the San Pedro. The river has entrenched itself fully 200 feet in these deposits, and as a result the alluvial slope has been extensively dissected by intermittent streams pouring from the adjacent mountains and hills.

The maximum thickness of the gravel deposits is unknown. Drilling northeast of Tiger, as previously noted, cut through 2,200 feet of gravel and conglomerate without reaching the rocks beneath. However, an unknown amount of this thickness probably belongs to the Gila(?) conglomerate.

RECENT ALLUVIUM

The San Manuel region is subject to torrential rainfall during a short period after midsummer. Accordingly, on the lower parts of steep slopes and hills there is some debris which is a combination of talus and alluvial wash.

The Gila(?) conglomerate is poorly cemented by an argillaceous matrix and readily breaks down, allowing a rubble to accumulate to a thickness of several feet. Actual exposures of the conglomerate are therefore confined mainly to stream channels where rapid erosion clears away the weathered debris.

Because of this confusion of gravels and conglomerate deposits, it is very difficult to separate them in mapping. In the present report the three deposits—the Gila(?)

conglomerate, the alluvial slope gravels, and Recent alluvium—have not been separated on the maps (fig. 3 and pl. 1). In the area of the earliest drilling a separation of the Gila(?) and the Recent alluvium and talus was made, but lack of time and a suitable base map for outlying areas made it desirable to abandon this distinction.

STRUCTURE

REGIONAL STRUCTURE

The San Manuel area is a part of the Black Hills, and the broad relations shown on geologic and topographic maps of Arizona indicate that they are a northward extension of the Santa Catalina Mountains, which rise 6,500 feet about the desert floor at Tucson. The northwest front of the Santa Catalina Mountains is bounded by the north-trending Santa Catalina fault, and the mountains have an imposing steep scarp along the northwest side. The fault is a normal one that dips steeply west. The Black Hills may be bounded on the west by a north-trending fault parallel to the Santa Catalina fault—or by an offset continuation of it. The broad trough occupied by the San Pedro River borders the east side of both the Santa Catalina Mountains and the Black Hills.

The east side of the San Pedro trough is bounded by the bold scarp of the Galiuro Mountains. This range is considered by Davis and Brooks (1930, pp. 89–115) to be a tilted and dissected fault block with the scarp descending 3,000 to 4,000 feet to the San Pedro trough which they believe is a typical intermontane trough that has been partly filled with alluvium and then trenched by the San Pedro River. The history of the alluvial slope deposits in this intermontane trough is somewhat more complex than indicated by Davis who does not refer to the highly tilted and faulted conglomerate overlain unconformably by the alluvial slope deposits.

The San Manuel area is part of a tilted block or structural ridge lying between the depressed San Pedro block and the down-faulted area along the west side of the Santa Catalina Mountains and the Black Hills. Later movement resulted in a series of faults with a general north-south strike and steep dips generally to the east. The San Manuel deposit lies near the east side of the block at the place where the older rocks that comprise the Black Hills emerge from the alluvial slope deposits of the San Pedro trough.

FAULTS

The most important structural features of the San Manuel area are faults that offset the conglomerate and all older rocks.

In drilling, many strong fracture zones were encountered that made further drilling impossible; and a num-

ber of holes, including H, U, 47, 61, 73, 80, and 105, had to be drilled anew because of severe caving at depths ranging from 777 to 1,265 feet. It may be safely inferred that shearing during faulting was responsible for much of this difficulty; gouge and slickensided rock furnished proof in some cases. In many places these weak zones were not related to known faults; this suggests that the massive igneous rocks might have been cut by faults earlier than the conglomerate and possibly earlier than the mineralization. In the absence of bedding or key units, it is impossible to judge from churn-drill cuttings whether these broken zones are faults or fissure zones with little or no displacement in the plane of the fracture.

An adit 150 feet long was driven in the diabase just west of hole 11 during an earlier exploration in the district. Many slickensided surfaces strike within 10° of $N. 75^\circ E.$, and most of them range in dip from vertical to $70^\circ N.$ The dike strikes about $N. 65^\circ E.$ The north side of the dike is a slickensided surface.

Float on the slopes of Red Hill often shows slickensided surfaces indicating movement in rocks where no faults are mapped. A pit just southeast of the crest of Red Hill exposed a prominent hematite-coated slickensided, and a similar occurrence was seen in Tucson Wash. These seem to be a result of postoxidation movement, as there is no evidence of hypogene hematite of this sort from the drilling below the zone of oxidation.

Large differences in the altitude of the zone of secondary sulfide enrichment between adjacent drill holes cannot be explained by faults of pre-Gila age, (?) because the pyritic zone beneath does not show a similar displacement. Clarification of such problems may have to await future study when extensive underground openings are made.

Several well-defined faults cut the San Manuel deposit and adjacent rocks. These are normal faults, but the earliest is of a low angle and was probably caused by rotation during tilting of the region. The others are high-angle faults, probably not all of the same age. Each fault will be described separately in some detail, and its relation to the deposit and the other faults explained.

SAN MANUEL FAULT

The San Manuel fault, named by geologists and engineers of the San Manuel Copper Corporation, is the most extensive fault known in the region. The fault crops out along the south side of Red Hill (center of pl. 1), and has been traced to a point about a mile west of Tucson Wash (pl. 3), and beyond the east edge of the mapped area (see fig. 1). It is well exposed in several small trenches and pits along its outcrop and particularly at a short inclined shaft close to the intersections of the zero coordinates of the grid (fig. 4). The

Gila(?) conglomerate dips toward the fault, and the lower fault cuts off a diabase dike that forms the general boundary at the outcrop between the copper-bearing rock and the weathered pyritic rock. The average dip of the fault is $30^\circ SW.$ near the outcrop and less to the southwest. The strike of the fault varies but is $N. 80^\circ W.$ between drill holes a few hundred feet from the outcrop of the ore zone.

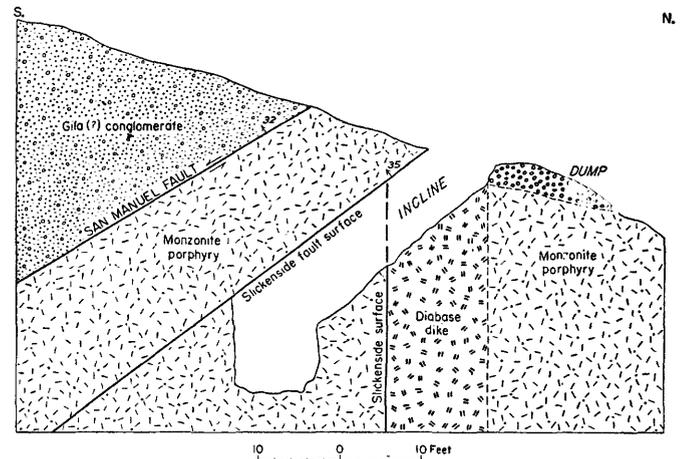


FIGURE 4.—Diagram of San Manuel fault and a subsidiary fault at inclined shaft near intersection of zero lines of drill grid.

At the southeast end of the outcrop of the ore zone the San Manuel fault is cut by the West fault (Steele and Rubly, 1947) which offsets the San Manuel fault about 1,500 feet horizontally at the surface. A dip slip of 460 feet on the West fault would account for two-thirds of the apparent horizontal displacement. Outcrops of a vertical diabase dike occur on the west side of the fault, and about 400 feet east are other small exposures of diabase approximately in line. This suggests a very small horizontal component to the movement on the West fault. Projection of the displaced San Manuel fault southeastward brings it against the East fault, and there, too, the San Manuel fault seems to have been displaced northward about 500 feet (pl. 1). The dip of the San Manuel fault is about 30° in this east block, or practically identical with its dip west of the West fault.

The San Manuel fault trends northwestward along the southwest side of Red Hill, passes south of shaft 1, and then trends westward along a gully down the steep slopes of Tucson Wash. Toward the bottom of Tucson Wash the tributary gully turns north of the fault and has cut a winding canyon in quartz monzonite. Near the mouth of the gully is a conspicuous fractured and slickensided fault zone, striking $N. 80^\circ W.$ and dipping $42^\circ S.$, which is in the footwall of the projection of the San Manuel fault. The San Manuel fault trends into a fault complex along the east wall of the wash where a tongue of conglomerate overlies quartz monzonite

between the fault zone noted above and the projection of the main fault. On the west side of Tucson Wash a mass of conglomerate overlies porphyry along an irregular south-dipping fault plane. About 1,600 feet to the west of Tucson Wash the fault is offset to the south about 400 feet by a cross fault (fig. 3). Detailed mapping by H. J. Steele has verified the existence of the fault for more than a mile west of Tucson Wash, and it may extend much farther.

The San Manuel fault persists with regularity in the area explored by churn drilling southwest of the trace of the fault; however, an unusual feature is the low dip of this normal fault. The fault probably formed in a period of deformation preceding the tilting of the conglomerate. The beds of the conglomerate over a wide area are known to dip to the northeast at angles ranging from 20° to 40°, and the average dip over the ore body is about 30°. When the conglomerate and other rocks were tilted 30° to the northeast, the southwest-dipping San Manuel fault was tilted a corresponding amount, thus reducing its original dip of slightly more than 60° to about 30°.

An even lower dip is indicated in shaft 2 (pl. 1), but the persistence of the fault over a wide area was verified. H. J. Steele (personal communication) reported the following observations in the shaft.

In shaft 2 at 702 feet below the collar we cut the conglomerate-porphphy contact which was a fault contact dipping 15°, plus or minus, to the southwest. It was a sharp break, with 5 to 7 feet of red gouge and the conglomerate in the hanging wall relatively undisturbed. The porphyry below the contact contained a series of faults more or less parallel to the San Manuel fault and the ground gave evidence of considerable shearing for 50 to 75 feet below the contact.

WEST FAULT

* The West fault is best exposed in a small exploration shaft low on the slope of Red Hill just north of drill hole 9, and its location is closely shown along the east side of the outcrop of the ore body at hole 1 by red and gray soils of the ore body and the Gila(?) conglomerate.

The strike of the fault is somewhat irregular, but it averages about N. 30° W. for most of its length, swinging to N. 5° W. at the north end (pl. 1). The dip is 60° to the east in the shaft near hole 9 but is steeper at hole 1 where the dip, as calculated from the base of the conglomerate in the hole to the outcrop of the fault, is 75°. Farther south at an outcrop near hole 51 the dip is 80°.

The vertical displacement on the West fault is about 400 feet, as indicated by the base of the Gila(?) conglomerate at the San Manuel fault on both sides of the fault (pl. 9A and C). The vertical displacement decreases southward as shown by the sections, and it is difficult to trace the fault because of the mantle of

decomposed conglomerate. Near hole 80 a fault that strikes N. 60° W. is poorly exposed in the banks of the dry wash. The dip is to the east at 70° to 80°, and except for a difference of about 35° in strike it displaces the rocks about as much as the West fault and may be a branch of that fault as is indicated on the map. About 700 feet farther south near shaft 2 another fault cuts across the extension of the West fault but dips west about 50°. Lack of good outcrops in the Gila(?) conglomerate makes it impossible to work out the details.

The West fault has been traced northward about 750 feet from hole 9 but all attempts to trace it farther have failed in spite of the fact that the rock exposures are relatively good. On plate 1 it appears possible that the northward extension of the fault may pass between a mass of monzonite porphyry on the west and quartz monzonite on the east, but evidence to support this extension is lacking.

EAST FAULT

The distribution of formations on the geologic map indicates that a fault must exist roughly parallel to the West fault and about 800 feet to the east of it. Unfortunately, exposures of this fault are very poor, but a fault zone in conglomerate does show in a gully just east of hole 63 and also along the bank of the large wash near hole 87.

To the north near Tiger the Mammoth fault as shown by Peterson (1938a, pl. 1) is exposed in a test pit just beyond the border of the geologic map in this report (pl. 1). It is difficult to trace the fault southward from this pit, especially across a gully where the rock is well exposed. South of the gully, however, near the secondary road from San Manuel to Tiger (coordinates 11,200 E., 13,780 N. on pl. 1), the contact of the conglomerate and quartz monzonite is essentially straight for a distance of 1,000 feet. This suggests a fault contact, with a nearly vertical dip. If the line of this part of the contact is projected southward, conglomerate appears both east and west of the projected line for some distance, but if the projection is continued southward, it lines up well with the East fault. Until excavations better reveal the undisturbed rocks in the area between the East fault and the known Mammoth fault near Tiger, the correlation should be considered tentative.

CHOLLA FAULT

The Cholla fault, named from the Cholla claims, is exposed near State Highway 77 in a gully near hole H5. Gila(?) conglomerate is separated from alluvial slope deposits by a foot of gouge. The fault strikes N. 40° W. and dips 80° NE. E. F. Reed traced this fault northwestward to a shallow shaft near the Tiger road where the fault is well exposed (pl. 1).

A very strong fault zone occurs in the southeast drifts and crosscuts of the St. Anthony mine where Gila(?) conglomerate is in fault contact with quartz monzonite. Projection of this fault to the surface places it in line with the Cholla fault to the south.

Near the Tiger road there is a difference of 300 feet in the altitude of the base of the conglomerate in drill holes H1 and H3 of the Houghton Group. Farther south the difference is 775 feet between Houghton Group holes H8 and H18. Inasmuch as the unconformable surface at the base of the conglomerate dips to the east, the known vertical displacement is somewhat less than 775 feet, but southward it may be more. It is important in exploration because a thick unit of conglomerate must be penetrated east of the Cholla fault in order to reach the potentially mineralized rocks beneath.

GEOLOGIC HISTORY

The interpretation of the geologic history from the rocks in and near the San Manuel district is decidedly incomplete, but by interpolation from areas within 50 miles that have been mapped in considerable detail, a moderately complete history may be deduced.

The oldest rock in the area is known only from a few xenoliths of biotite schist cut by drill holes in quartz monzonite. This rock is doubtless pre-Cambrian and may be a fragment of Pinal schist. The oldest abundant rock is the quartz monzonite (Oracle granite), and it occurs over a wide area between Oracle and San Manuel and in the northern part of the Santa Catalina Mountains. The large size of the granite terrane, extensive exposures, the coarseness of grain, and the extensive aplitic facies indicate a large deep-seated intrusive mass. A long period of erosion followed the intrusion of the batholith, as is shown by the fact that the Scanlon conglomerate at the base of the pre-Cambrian Apache group lies unconformably on the quartz monzonite (Darton, 1925, p. 281). The Apache group is not exposed in the San Manuel area but crops out in Camp Grant Wash to the north, as well as in the Santa Catalina Mountains to the south. It is certain, then, that sedimentation was rapid in the region during late pre-Cambrian time. Either the San Manuel area was an island or these Apache sediments were deposited over it and later eroded from the quartz monzonite. In the Santa Catalina Mountains, sedimentary rocks of Cambrian, Devonian, and Carboniferous age occur above the Apache group. This suggests that the Paleozoic was a time of intermittent invasions by epicontinental seas. Probably some of the sediments of the Paleozoic era were laid down in the San Manuel area but were stripped off by erosion during Mesozoic time, because no sedimentary rocks of this age are known in

the area. There is a possibility that some of the volcanic and associated fragmental rocks of the area are Cretaceous. At least one period of intrusion and two periods of ore deposition occurred during the Mesozoic or early Tertiary. A period of rhyolitic intrusion followed the pouring out of the basalt lavas and preceded the deposition of the Gila(?) conglomerate.

The main period of faulting in the Ray and Miami districts came after the intrusion of diabase, and this may well be true at San Manuel, 25 miles south of Ray. A period of mountain building must have taken place in Tertiary time, because the Gila(?) conglomerate that lies unconformably on the eroded igneous rocks at San Manuel gives abundant evidence of vigorous erosion on steep slopes, and rock of local derivation forms most of the pebbles and boulders in many places. Volcanic ash falls also occurred at one or more periods, as shown by beds of tuff interbedded with the conglomerate beds. The Gila conglomerate is usually assigned to late Tertiary and early Quaternary, but the correlation is questionable. In any event, the Gila(?) conglomerate at San Manuel was broken by a complex series of faults and tilted to the northeast.

Considerable erosion occurred after tilting of the Gila(?) conglomerate, and the alluvial slope deposits of the San Pedro trench were laid down on the eroded Gila(?) conglomerate. Uplift or other physiographic changes caused the San Pedro River to cut a deep valley in alluvial deposits, and tributary drainage has dissected the alluvial slope to a marked degree. Renewal of faulting in relatively recent geologic time is indicated by down-faulted San Pedro alluvial slope deposits against Gila(?) conglomerate along the Cholla fault. Recent alluvial deposits have accumulated to some extent in the tributary washes and formed a considerable flood plain along the San Pedro River.

ROCK ALTERATION

All the rocks below the Gila(?) conglomerate are hydrothermally altered to various degrees throughout the San Manuel and adjacent areas. There is a direct relation between the type of hydrothermal alteration and the occurrence of copper; so, an understanding of the alteration is essential in exploration and development of the ore in the area. More than 200 thin sections of exposed rocks and chips from drill cuttings were examined, and many X-ray diffraction patterns were made to verify determinations of the fine-grained minerals of the clay group. Rock analyses were made by the Geological Survey, and many analyses of composite samples were made available by the Bureau of Mines and by the San Manuel Copper Corporation assay laboratories.

The writer visited all the important producing disseminated copper deposits in the western United States (Schwartz, 1947, pp. 319-352) and compared them with the San Manuel deposit, particularly as to character of hydrothermal alteration. He also conferred with T. S. Lovering who made available, in advance of publication, a table of alteration minerals with their important optical properties (Lovering, and others 1949, fig. 12). The minerals discussed in this section correspond to those of Lovering's table.

The area around the San Manuel copper deposit shows unusually clear evidence of four types of hydrothermal alteration. These are designated by minerals characteristic of each type.

Kaolinite-alunite alteration (type 1).

Hydromica-pyrite alteration (type 2).

Sericite-pyrite-chalcopyrite alteration (type 3).

Marginal biotite alteration (type 4).

All four types of altered rock may be seen within a comparatively small area where the pre-Gila(?) rocks are exposed at the site of the first drill holes (pl. 1) and northward toward Tiger. The four types appear to occupy moderately well-defined zones, which were shown on the preliminary maps (U. S. Geol. Survey Strategic Minerals Investigations, Preliminary Maps 3-180, April 1945). The space relations as now understood, based on extensive drilling and outcrops, are shown on plate 8. The minerals in each zone are shown in table 1.

The kaolinite-alunite type forms an oval-shaped zone about 700 feet wide by 1,000 feet long lying north of hole 77. The extension of the zone to the east is hidden beneath the Gila(?) conglomerate. The hydromica-pyrite zone surrounds the kaolinite-alunite zone and forms a wide belt centering about Red Hill but known to extend both eastward and southwestward beneath the beds of the Gila(?) conglomerate. It swings around the east end of the deposit and appears on the south side (pl. 8). The sericite-pyrite-chalcopyrite type of altered rock (the ore zone) forms a narrow belt southeast of Red Hill but broadens out eastward as shown on the maps (fig. 8 and pl. 8). The marginal biotite zone occurs north of the hydromica-pyrite zone and south of the ore zone.

The horizontal pattern is incomplete, for drilling of the Houghton Group east of the San Manuel property (pl. 8) shows that the area of hydromica-pyrite rock extends eastward beyond the area now drilled. More than 1,100 feet of conglomerate overlies the pyritic rock there, and further exploration will doubtless be difficult and expensive. The hydromica-pyritic alteration also extends an unknown distance south of the eastern part of the San Manuel ore body, and the hole farthest south of the drill grid, no. 100, is in the hydromica-

pyritic type from the base of the conglomerate at 475 feet to the bottom of the hole at 2,500 feet. Nothing is known of the extension of this alteration southward beneath the conglomerate, except that monzonite porphyry exposed about a mile to the southwest is only moderately altered (marginal biotite type). Judging from the widespread nature of the alteration and the uncertainties involved because of the heavy cover of conglomerate, it seems best not to postulate concentric zones of alteration except as these happen to exist in the exposed area.

KAOLINITE-ALUNITE ALTERATION (TYPE 1)

The most intensely altered rocks found at the surface are in a small area directly east of Red Hill and immediately north of the east-central part of the copper ore body (pl. 8). These rocks consist mainly of kaolinite, alunite, and quartz. The surface exposure of this zone is slightly oval, with the long axis east-west; the dimensions are approximately 700 by 800 feet. The south side of the oval area is concealed by a faulted segment of Gila(?) conglomerate, but the gradation to other types is exposed except at the east end where the conglomerate overlies the altered monzonite porphyry and quartz monzonite. The distance this zone extends eastward is unknown, but the shape of the exposed part indicates that it does not extend far.

At the surface, rock of the kaolinite-alunite type is conspicuous because of its light-gray, almost white, color, contrasting with the prevailing red of most of the other rocks. The rock ranges from a very light gray to a weak purple on some fracture surfaces. It is often minutely veined or fractured; the fractures are occupied by iron oxides, and minute specks of iron oxide are also disseminated throughout the darker specimens. The amount of iron oxide concentrated in the fractures is relatively large; analysis of kaolinite-alunite rock (no. 1, table 2, p. 25) shows 7.12 percent Fe_2O_3 .

Unfortunately, no drill hole is located where rock of this type crops out. Drill hole 77 is on the border as shown on plate 8, but examination of the cuttings revealed no rock at depth that could be definitely related to this zone. Unoxidized specimens of this zone of alteration are not available for microscopic study, but, locally, similar rock occurs in the hydromica-pyrite zone. The rock exposed within the oval area is highly altered monzonite porphyry and some quartz monzonite cut by a rhyolite dike.

The porphyritic texture of the rock is obscured by the fine-grained alteration products, but faint outlines remain of some feldspar and biotite phenocrysts. Much of the rock appears crackled because of a network of very minute veinlets (pl. 2A).

TABLE 1.—Secondary minerals present in thin sections of hydrothermally altered rocks, San Manuel copper deposit, Arizona
[Cross indicates presence of mineral. Sulfides not shown]

| Drill hole or specimen | Depth (feet) | Quartz | Sericite | Hydromica | Potash clay | Kaolinite | Allophane | Alunite | Blotite ¹ | Hydrobiotite | Chlorite | Epidote | Clinzoisite | Calcite | Rutile | Leucocene | Barite | Beidellite | Dickite | Endellite | Fluorite | Halloysite | Montmorillonite | Nontzonite | Orthoclase | Sphene |
|--|--------------|--------|----------|-----------|-------------|-----------|-----------|---------|----------------------|--------------|----------|---------|-------------|---------|--------|-----------|--------|------------|---------|-----------|----------|------------|-----------------|------------|------------|--------|
| Kaolinite-Alunite Alteration: Type 1 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| In monzonite porphyry | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 ² | | X | X | X | X | X | X | X | | | | | | | X | X | | | X | | | X | | | | |
| 114 ² | | X | X | X | X | X | X | X | | | X | | | | X | X | | | X | | | X | | | | |
| 15 ² | | X | X | X | X | X | X | X | | | | | | | X | X | | | | | | X | | | | |
| 16 ² | | X | X | X | X | X | X | X | | | | | | | X | X | | | | | | X | | | | |
| 22 ² | | X | X | X | X | X | X | X | | | | | | | X | X | | | | | | X | | | | |
| 204 ² | | X | X | X | X | X | X | X | | | | | | | X | X | | | | | | X | | | | |
| In quartz monzonite | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 39 ² | | | | | | X | | X | | | | | | | | | X | | | X | | | | | | |
| Hydromica-Pyrite Alteration: Type 2 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| In monzonite porphyry | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 ² | | | X | | | X | X | X | | | | | | | | X | | | X | | | | X | | | |
| 21 ² | | X | X | X | | X | X | X | | | | | | | X | X | | | X | | | | | | | |
| 9 | 650 | X | X | X | | X | X | | | X | X | | | | X | X | X | | X | | X | | | | | |
| 9 | 660 | X | X | X | | X | X | | | X | X | | | | X | X | | | X | | X | | | | | |
| 11 | 670 | X | X | X | | X | X | | X | X | X | | | | X | X | | | X | | | | X | | | |
| 11 | 700 | X | X | X | | X | X | | X | X | X | | | | X | X | | | X | | | | X | | | |
| 16 | 260 | X | X | X | | X | X | | X | X | X | | | | X | X | | | X | | | | | | | |
| C | 540 | X | X | X | X | | | X | | | | | | | X | | | | X | | | | | X | | |
| 93 | 625 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| 93 | 1,050 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| H2 | 275 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| H2 | 930 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| H2 | 1,300 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| H3 | 1,300 | X | X | X | X | | X | X | X | X | | | | | X | X | | | | | | | | | X | |
| H3 | 1,340 | X | X | X | X | | X | X | | | | | | | X | X | | | | | | | | | | |
| H4 | 1,865 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| H8 | 1,050 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| 52 | 1,635 | X | X | X | X | | X | | | | X | | | | X | X | | | | | | | | | | |
| In quartz monzonite | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 ² | | | X | X | | | | | | X | | X | | | | X | | | | | | | | X | | |
| C | 490 | | X | X | | | | | | | | | | | X | X | | | X | | | | X | | X | |
| C | 655 | X | X | X | X | | X | | | | | | | | X | X | | | X | | | | | | | |
| N | 420 | X | X | X | | | X | | | | | | | | X | X | | | | | | | | | | |
| N | 430 | X | X | X | | | X | | | | | | | | X | X | | | | | | | | | | |
| N | 640 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| N | 665 | X | X | X | X | | X | | X | X | | | | | X | X | | | | X | | | | | | X |
| | 49 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | |
| | 38 | X | X | X | X | | X | | | | X | | | | X | X | | | | | | | | | | |
| Sericite-Pyrite-Chalcopyrite Alteration: Type 3 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| In monzonite porphyry | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 ² | | X | X | X | | X | | | X | X | | | | | | X | | | | | | | | | | |
| 10 ² | | X | X | X | | X | | | | | X | | | | | X | | | | | | | | | | |
| 18 ² | | X | X | X | | | X | | | | | | | | | X | | | | | | | | | | |
| 42 ² | | X | X | X | | | | | | | | | | X | | X | | | | | | | | | | |
| 3 | 445 | X | X | X | | | | | | | | | | | X | X | | | | | | | | | | |
| 4 | 415 | X | X | X | | X | X | | | X | X | X | X | X | X | X | | | X | | | | | | | |
| 4 | 510 | X | X | X | X | | X | | X | X | | | | | X | X | | | | | | | | | | |
| 6 | 1,100 | X | X | X | X | | X | | X | X | | | | | X | X | | | | | | | | | | |
| 6 | 1,105 | X | X | X | X | | X | | X | X | | | | | X | X | | | | | | | | | | |
| 6 | 1,260 | X | X | X | X | | X | | X | X | | | | | X | X | | | | | | | | | | |
| 12 | 1,110 | X | X | X | X | | X | | | | X | | | | X | X | | | | | | | | | | |
| 14 | 430 | X | X | X | X | | | | X | X | X | X | | | X | X | | | | | | | | X | | |
| 14 | 630 | X | X | X | X | | | | X | X | X | X | | | X | X | | | X | | | | | X | | |
| 14 | 680 | X | X | X | X | | | | X | X | X | X | | | X | X | | | | | | | | X | | |
| 14 | 695 | X | X | X | X | | | | X | X | X | X | | | X | X | | | | | | | | X | | |

See footnotes at end of table.

TABLE 1.—Secondary minerals present in thin sections of hydrothermally altered rocks, San Manuel copper deposit, Arizona—Continued

| Drill hole or specimen | Depth (feet) | Quartz | Sericite | Hydromica | Potash clay | Kaolinite | Allophane | Alumite | Biotite 1 | Hydrobiotite | Chlorite | Epidote | Clinzoisite | Calcite | Rutile | Leucosene | Barite | Beldellite | Dickite | Endellite | Fluorite | Halloysite | Montmorillonite | Nontronite | Orthoclase | Sphene | |
|--|--------------|--------|----------|-----------|-------------|-----------|-----------|---------|-----------|--------------|----------|---------|-------------|---------|--------|-----------|--------|------------|---------|-----------|----------|------------|-----------------|------------|------------|--------|--|
| Sericite-Pyrite-Chalcopyrite Alteration: Type 3—Continued | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| In monzonite porphyry | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| A | 800 | | X | X | X | X | | | | X | X | | | | X | X | | | | | | | | | | | |
| B | 480 | X | X | X | X | X | | | X | X | X | | | | X | X | | | | | | | | | | X | |
| B | 500 | X | X | X | X | X | X | | X | X | X | | | | X | X | | | | | | | | | | | |
| I | 1,370 | X | X | X | | X | | | | X | | | | | X | X | | | | | | | | | | | |
| Q | 1,380 | X | X | X | | X | X | | | X | X | | | X | X | X | | | | | | | | | | | |
| 44 | 1,595 | | X | X | | X | X | | | X | | | | | X | X | | | | | | | | | | | |
| 50 | 1,935 | X | X | X | | X | | | | | X | | | | X | X | | | | | | | | | | | |
| 52 | 1,635 | | X | X | | X | | | | | X | | | | X | X | | | | | | | | | | | |
| 84 | 1,575 | | X | X | X | X | X | | | | | | | | X | X | | | | | | | | | | | |
| 87 | 370 | X | X | X | | X | | | | | | | | | X | X | | | | | | | | | | | |
| 89 | 1,520 | X | X | X | X | X | | | | | | | | | X | X | | | | | | | | | | | |
| H5 | 1,075 | X | X | X | X | X | | | | X | | | | | X | X | | | | | | | | | | | |
| H5 | 1,150 | X | X | X | | X | X | | | | | | | | X | X | | | | | | | | | | | |
| H5 | 1,250 | X | X | X | | X | | | | | X | | | | X | X | | | | | | | | | | | |
| H5 | 1,272 | X | X | X | | | X | | | | X | | | | X | X | | | | | | | | | | | |
| H5 | 1,275 | X | X | X | | | | | | | X | | | | X | X | | | | | | | | | | | |
| H5 | 1,300 | | X | X | | | | | | X | X | | | | X | X | | | | | | | | | | | |
| H5 | 1,350 | X | X | X | | X | | | X | X | X | | | | X | X | | | | | | | | | X | | |
| H5 | 1,425 | X | X | X | | | X | | | X | X | | | | X | X | | | | | | | | | | | |
| H5 | 1,500 | | X | X | | | | | | | | | X | | X | X | | | | | | | | | | | |
| H5 | 1,650 | X | X | X | | X | | | | | | | | | X | X | | | | | | | | | | | |
| H5 | 1,410 | X | X | X | | X | | | | X | X | | | | X | X | | | | | | | | | | | |
| H6 | 1,226 | | X | X | | X | | | | | | | | | X | X | | | | | | | | | | | |
| H7 | 725 | | X | X | | X | | | | | | | | | X | X | | | | | | | | | | | |
| H7 | 1,395 | | X | X | | X | | | | X | X | | | | X | X | | | | | | | | | | | |
| 5 | 605 | | X | X | | X | | | X | X | X | X | | | X | X | | | | | | | | X | | | |
| 5 | 635 | X | X | X | X | | | | X | X | X | | | | X | X | | | X | | | | | X | | | |
| 5 | 690 | X | X | X | | X | | | X | X | X | | | | X | X | | | X | | | | | | | | |
| C | 640 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | | |
| 5 | 700 | X | X | X | X | X | | | | X | X | | X | | X | X | | | | | | | | | | | |
| 16 | 260 | | X | X | | X | | | | X | X | | | | X | X | | | | | | | | | | | |
| 84 | 400 | X | X | X | X | X | | | X | X | X | | | | X | X | | | | | | | | | | | |
| In quartz monzonite | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 ² | | | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | | |
| 38 ² | | | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | | |
| 2 | 1,135 | X | X | X | | X | X | | | | | X | | | X | X | | X | | | | | | | | | |
| 4 | 815 | X | X | X | | | | | | | | X | | | X | X | | | | | | | X | | | | |
| 4 | 870 | X | X | X | | | X | | | | | X | | | X | X | | | | | | | X | | | | |
| 4 | 1,000 | X | X | X | X | | X | | | | | X | | | X | X | | | | | | | | | X | | |
| 12 | 1,395 | | X | X | X | X | X | | | X | | | | | X | X | | | | | | X | | | | | |
| 15 | 1,790 | | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | | |
| 15 | 1,795 | X | X | X | | | X | | X | X | | | | | X | X | | | | | | | | | | X | |
| 15 | 1,805 | X | X | X | | | X | | X | X | X | | | | X | X | | | | | | | | | | X | |
| 15 | 1,870 | X | X | X | | | X | | X | X | X | | | | X | X | | | | | | | | | | X | |
| 15 | 1,900 | X | X | X | X | | X | | | | | | | | X | X | | | | | | | | | | X | |
| 15 | 1,985 | X | X | X | | | | | | X | X | | | X | X | X | | | | | | | | | | X | |
| A | 1,100 | X | X | X | | | | | | | X | | | | X | X | | | | | | | | | | X | |
| C | 250 | X | X | X | | X | | | | | | | | | X | X | X | | | | X | | | | | | |
| I | 1,450 | X | X | X | | X | X | | | X | X | | | | X | X | X | X | | | X | | | | | | |
| I | 1,456 | | X | X | X | | | | X | X | X | | | | X | X | | | | | | | | | | | |
| I | 1,470 | X | X | X | | | | | X | X | X | | | | X | X | | | | | | | | | | X | |
| K | 1,220 | X | X | X | | | | | X | X | X | | | | X | X | | | | | | | | | | | |
| Q | 1,635 | | X | X | | | X | | | X | X | | | | X | X | | | | | | | | | | | |
| S | 1,170 | | X | X | | | X | | | X | X | | | | X | X | | | | | | | | | | | |
| S | 1,175 | X | X | X | | | X | | | X | X | | | | X | X | | | | | | | | | | | |
| U | 2,180 | X | X | X | | X | X | | | X | X | | | | X | X | X | | | | | | | | | | |
| Y | 2,090 | X | X | X | | X | | | X | X | X | | | | X | X | | | | | | | | | | | |
| 45 | 2,210 | X | X | X | | X | X | | | X | X | | | | X | X | | | | | | | | | | | |
| 46 | 1,270 | | X | X | | X | X | | | X | X | | | | X | X | | | | | | | | | | | |
| 51 | 2,345 | X | X | X | | X | X | | X | X | X | | | | X | X | | | | | | | | | | | |
| 58 | 1,535 | X | X | X | | X | X | | | | | | | | X | X | | | | | | | | | | | |
| 62 | 295 | | X | X | | X | X | | | | | | | | X | X | | | | | | | | | | | |
| 80 | 2,160 | | X | X | | | | | X | | | | | | X | X | | | | | | | | | | | |
| 93 | 1,830 | X | X | X | X | | | | | | X | | | | X | X | | | | | | | | | | | |
| H6 | 1,330 | | X | X | | | | | | | | | | | X | X | | | | | | | | | | | |

See footnotes at end of table.

TABLE 1.—Secondary minerals present in thin sections of hydrothermally altered rocks, San Manuel copper deposit, Arizona—Continued

| Drill hole or specimen | Depth (feet) | Quartz | Sericite | Hydromica | Potash clay | Kaolinite | Allophane | Alunite | Biotite ¹ | Hydrobiotite | Chlorite | Epitote | Clinozoisite | Calcite | Rutile | Leucosene | Barite | Beldellite | Dickite | Endellite | Fluorite | Halloysite | Montmorillonite | Nontronite | Orthoclase | Sphene |
|--|--------------|--------|----------|-----------|-------------|-----------|-----------|---------|----------------------|--------------|----------|---------|--------------|---------|--------|-----------|--------|------------|---------|-----------|----------|------------|-----------------|------------|------------|--------|
| Sericite-Pyrite-Chalcopyrite Alteration: Type 3—Continued | | | | | | | | | | | | | | | | | | | | | | | | | | |
| In quartz monzonite—Continued | | | | | | | | | | | | | | | | | | | | | | | | | | |
| H6 | 1, 400 | | X | X | | | | | | | | | | | X | | | | | | | | | | | |
| 77 | 925 | X | X | X | X | X | | | | | | | | | X | | X | | | | | | | | | |
| H6 | 1, 280 | | X | | | X | | | | | | | | | X | | X | | | | | | | | | |
| Marginal Biotite Alteration: Type 4 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| In monzonite porphyry | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 ² | | X | X | | | | | | | | X | X | X | X | | X | | | | | | | | | | |
| 36 ² | | | X | X | | | | | | | X | X | X | X | X | | | | | | | | | | | |
| 37 ² | | X | X | X | | | | | | | X | X | X | X | X | | | | | | | | | | | |
| 6 | 1, 260 | X | X | X | | X | | | X | X | | | | X | X | X | | | | | | | | | | |
| 5 | 885 | X | X | X | X | | | | | | | | | | X | | | | | | | | | | | |
| 7 | 370 | X | X | X | | | | | X | X | X | | X | X | X | X | | | | | | | | | | |
| 7 | 605 | X | X | X | X | | X | | X | X | X | | X | X | X | X | | | | | | | | | | |
| 7 | 625 | X | X | X | | X | | | X | X | X | | X | X | X | X | | | | | | | | | | |
| 12 | 295 | X | X | X | | X | | | X | X | X | X | | X | X | | | | | | | | | | | |
| 12 | 320 | X | X | X | | X | | | X | X | X | | | X | X | | | | | | | | | | | |
| 12 | 535 | X | X | X | | X | | | X | X | X | | | X | X | | | | | | | | | | | |
| 14 | 325 | X | X | X | | | | | X | X | X | | | | X | | | | | | | | | | | |
| 14 | 390 | X | X | X | X | | | | X | X | X | | | | X | | | | | | | | | | X | |
| G | 870 | X | X | X | | | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| G | 1, 250 | X | X | X | X | | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 740 | X | X | X | X | X | | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 745 | X | X | X | | X | | | X | X | X | | | | X | X | X | | | | | X | | | | |
| H | 785 | X | X | X | X | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 840 | X | X | X | | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 845 | X | X | X | X | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 865 | X | X | X | | X | | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 890 | X | X | X | | X | | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 965 | X | X | X | X | | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 970 | X | X | X | X | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 1, 020 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| H | 1, 075 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| M | 295 | X | X | X | X | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| P | 645 | X | X | X | | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| Q | 1, 175 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | X | |
| T | 880 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| V | 850 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| Z | 735 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| Z | 825 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 44 | 1, 615 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 45 | 625 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 45 | 715 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 45 | 755 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 53 | 1, 220 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 53 | 1, 250 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 45 | 1, 225 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 46 | 1, 165 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 48 | 795 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 48 | 950 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 49 | 925 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 49 | 1, 015 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 49 | 1, 385 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 53 | 1, 220 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 53 | 1, 250 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 55 | 355 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 60 | 1, 210 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 65 | 240 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 80 | 1, 485 | X | X | X | X | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 3 ² | | X | X | X | | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| 24 ² | | X | X | X | | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| 44 ² | | X | X | X | | | | | X | X | X | | | | X | X | X | | | | | | | | | |
| 6 | 1, 260 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| 17 | 495 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |
| T | 880 | X | X | X | | X | X | | X | X | X | | | | X | X | X | | | | | | | | | |

¹ Recrystallized.

² Sample number.

Thin sections of the rock show a complex assemblage of minerals, but the most abundant are kaolinite, alunite, and quartz. The complete list of contained minerals, approximately in order of abundance, is: kaolinite, alunite, quartz, hydromica, allophane, rutile, limonite, hematite, jarosite, sericite, potash clay, halloysite, chlorite, dickite, leucoxene, barite, and endellite.

In some thin sections excellent pseudomorphs consist mainly of kaolinite after plagioclase. The kaolinite is an extremely fine-grained mat of flakes, and small amounts of other fine-grained products commonly occur with it, particularly allophane. One thin section contained a veinlet of kaolinite and allophane that clearly cut a fine mat of alunite and potash clay. Considerable amounts of halloysite occur with kaolinite in some thin sections, and small amounts of dickite were also recognized. Seams of potash clay cut some kaolinite pseudomorphs, and hydromica veinlets and flakes cut all of the other clay minerals.

Quartz is mainly fine grained and part is residual from the quartz-orthoclase mosaic of the primary groundmass. Grains of secondary quartz are abundant and much like the primary grains except that flakes of hydromica are enclosed. Where large quartz grains occur, they show in some thin sections an outer zone with wavy extinction, which contains inclusions of quartz with a different extinction. The inclusions are interpreted as primary, unaltered quartz, and the outer part as hydrothermal quartz, either introduced or recrystallized.

Part of the alunite is extremely fine-grained and is difficult to resolve with the microscope in some specimens in which X-ray tests prove its presence. In several thin sections, alunite pseudomorphs after plagioclase are relatively coarse grained (pl. 2B) and can be easily recognized by a moderate birefringence and negative elongation. Alunite has replaced orthoclase in the groundmass in some of the thin sections and perhaps in all of them. It also occurs as a veinlet with dickite in one section; in another it forms tiny veinlets of high relief. In two sections alunite occurs as zones around nuclei of iron oxide with square outlines. The iron oxide was doubtless derived from pyrite around which alunite formed a rim, as has been previously described (Grout and Schwartz, 1927, p. 372). Hexagonal pseudomorphs after biotite consist of aggregates of alunite, rutile, and the alteration products of pyrite-limonite and jarosite.

Hydromica occurs in all thin sections of the kaolinite-alunite type of rock. It ranges from abundant flakes forming aggregates to a few isolated flakes in kaolinite. It is more common than sericite with which it is associated in some sections.

Sericite is a very minor constituent in some specimens

and is lacking in others. One specimen contains a moderate amount of small flakes of sericite with more abundant hydromica; however, an X-ray analysis of this material shows that alunite, kaolinite, and quartz are the most abundant minerals. In thin sections sericite was observed to form stringers and veinlets in kaolinite, also isolated flakes of sericite occur embedded in a fine-grained mat of kaolinite without any evidence of alteration along the edges. The conclusion seems justified that some of the sericite flakes grew in the kaolinite essentially as metacrysts.

Biotite was a primary constituent of the rock but has been completely altered to pseudomorphs of sericite or clay minerals, with the expulsion of titanium that crystallized as rutile usually forming clusters or aggregates of minute grains in former areas of biotite. Leucoxene is also abundant in some thin sections.

Allophane is present in all thin sections and clouds the other minerals at places. It also occurs in veinlets. Veinlets of halloysite cut practically all other minerals and many are associated with limonite and are of supergene origin.

Jarosite, limonite, and red iron oxide, probably a mixture, are present to varying extents in all specimens. Before oxidation, pyrite was present locally as veinlets and as minute grains disseminated throughout the rock.

The paragenesis of this mass of alteration products, where the effects of weathering are superimposed on hydrothermal products, is difficult to determine. The various clay minerals including hydromica, kaolinite, and halloysite seem to have formed as a complex alteration of feldspar, and the amount of potassium available doubtless determined the specific mineral. The hydrothermal origin of clay minerals is shown by late quartz-sericite-pyrite veinlets that cut across the pseudomorphs of clay minerals after feldspar. Some relatively coarse-grained alunite, with kaolinite, formed pseudomorphs after oligoclase, and no age difference was determined; however, late in the hydrothermal stage alunite also was formed as veinlets and occurs to the greatest depth drilled to date.

The possibility that some of the kaolinite and alunite is a product of meteoric solutions is recognized. Part of the alunite is very fine-grained and probably is meteoric in origin, but much alunite occurs as relatively well-developed crystals (pl. 2B), and this is believed to be of hydrothermal origin. In a thin section of an alunitized dike on the north slope of Red Hill, alunite crystals project into pyrite, and a few are entirely enclosed by pyrite (pl. 2C). The relation suggests that the pyrite was molded around the alunite. A thin section of altered porphyry from the south slope of Red Hill shows veinlets of sericite cutting across both kaolinite and alunite.

A thin section of rock from a depth of 1,340 feet in hole H3 of the Houghton Group shows that feldspar has been in effect altered to a complex mat of sericite, hydromica, kaolinite, and alunite. Alunite occurs as relatively large crystals. These were observed to be penetrated by sericite flakes, and both are intimately associated with pyrite. One large platy grain of alunite was enclosed on three sides by pyrite. Kaolinite appears to have been an early hydrothermal product and alunite, sericite, and pyrite late products. The evidence seems conclusive that much alunite is hydrothermal and is, at least in part, earlier than pyrite and sericite.

Halloysite is the only clay mineral associated with limonite and some opal in the latest veins, and it is believed to be supergene in large part. Some halloysite, however, is an early hydrothermal mineral of zones of moderate argillic alteration, as has been shown at Tintic (Lovering and others, 1949, p. 17), and some of the halloysite at San Manuel seems to belong to this class.

The approximate mineral composition of the rock of the kaolinite-alunite and other types of alteration has been estimated from chemical analyses, and comparisons are shown in figure 5.

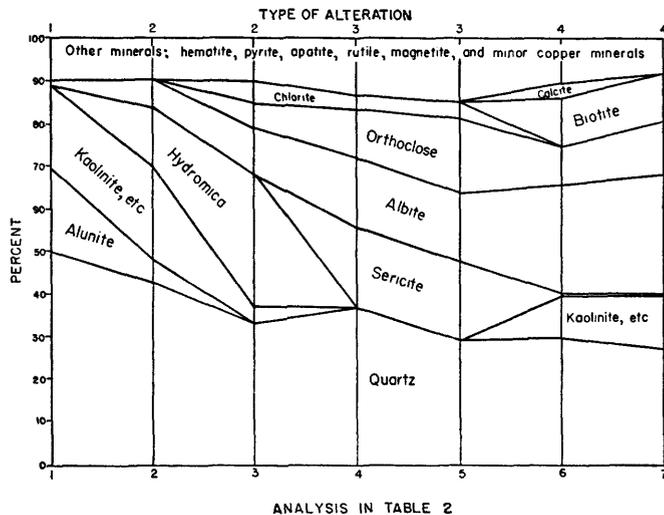


FIGURE 5.—Diagram of approximate percents of minerals in the four types of alteration of monzonite porphyry as calculated from analyses.

The chemical composition of monzonite porphyry that has altered to the kaolinite-alunite type is shown by analysis 1 in table 2. The material for this sample was selected along the dry wash northwest of hole 77. The analysis verifies most of the conclusions based on microscopic examination of thin sections. The amount of sulfate, 7.45 percent, indicates a possible alunite content as great as 19.3 percent, kaolinite comprises 19.17 percent, and quartz 50.28 percent—a total for the

three minerals of 88.75 percent. Iron oxides make up 7.18 percent, and the remainder is largely rutile, apatite, and moisture.

The percent of silica is lower than in the least altered porphyry, and the milligrams of silica per cubic centimeter in the kaolinite-alunite rock is 1,331 as compared with 1,679 in rock from hole H in the marginal biotite zone, (analysis 6, table 2). Ferric oxide content is notably higher; and lime, magnesia, and soda are very low. The potash content, 2.20 percent, is somewhat below that of the least altered porphyry (analyses 6 and 7, table 2), as might be expected from the high kaolinite content. The variation of some of the oxides among the four types of alteration is shown by diagram (fig. 6). The specific gravity of the bulk sample from which analysis 1 was made is 2.25; so the percentages of oxides are somewhat high for a direct comparison with the other analyses but lack of densities of bulk samples from drill holes makes a more precise comparison impossible.

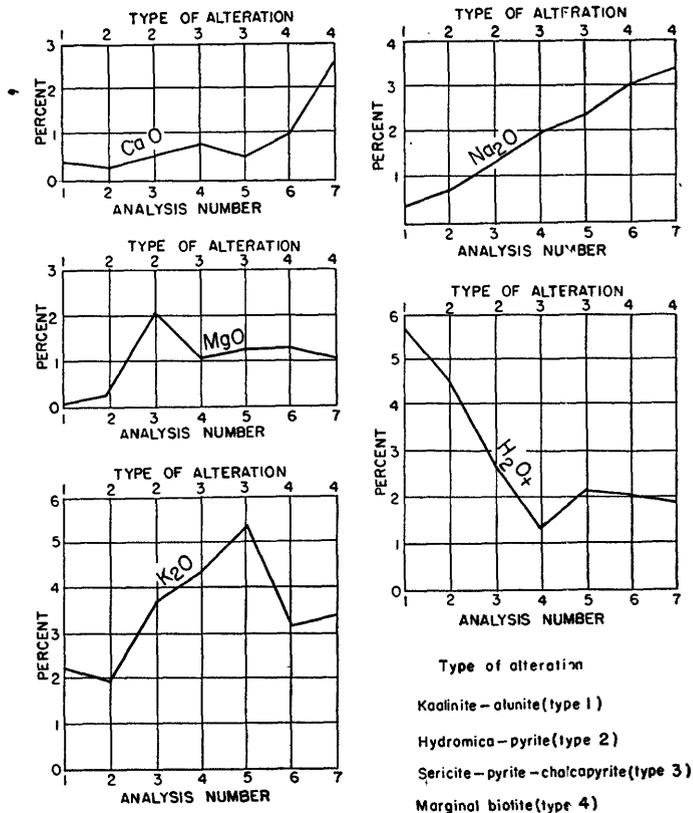


FIGURE 6.—Diagram of the variation in percent of oxide in analyses of rock from four types of alteration of monzonite porphyry. Analyses are given in table 2.

HYDROMICA-PYRITE ALTERATION (TYPE 2)

Almost surrounding the exposed area of kaolinite-alunite alteration is a zone characterized at the surface by a moderate red color. At depth the rock contains an abundance of disseminated pyrite, with hydromica as an important hydrothermal mineral. The area of this rock has been shown to be extensive, and Red Hill

TABLE 2.—Analyses of samples of monzonite porphyry representative of the four types of alteration

[Analyst Charlotte M. Warshaw]

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|--------------------------------------|-------|-------|-------|-------|-------|-------|-------|
| SiO ₂ ----- | 59.19 | 65.64 | 64.09 | 66.05 | 66.98 | 64.88 | 67.58 |
| Al ₂ O ₃ ----- | 14.71 | 15.95 | 15.50 | 14.12 | 15.32 | 15.01 | 15.10 |
| Fe ₂ O ₃ ----- | 7.12 | 6.61 | 2.98 | 2.24 | 1.87 | 1.06 | 1.83 |
| FeO----- | .32 | .48 | | | 1.13 | 2.42 | 2.20 |
| MgO----- | .08 | .28 | 2.03 | 1.10 | 1.33 | 1.44 | 1.07 |
| CaO----- | .42 | .27 | .53 | .77 | .50 | 2.59 | .94 |
| Na ₂ O----- | .40 | .72 | 1.36 | 1.91 | 2.33 | 3.02 | 3.42 |
| K ₂ O----- | 2.20 | 1.95 | 3.69 | 4.37 | 5.29 | 3.14 | 3.42 |
| H ₂ O+----- | 5.73 | 4.58 | 2.76 | 1.34 | 2.15 | 2.03 | 1.91 |
| H ₂ O----- | .86 | .34 | .49 | .17 | .46 | .37 | .32 |
| TiO ₂ ----- | .72 | .48 | .73 | .57 | .60 | .56 | .56 |
| P ₂ O ₅ ----- | .26 | .22 | .28 | .22 | .20 | .19 | .21 |
| MnO----- | .003 | .008 | .02 | .02 | .04 | .04 | .03 |
| CuO----- | .021 | .038 | .33 | 1.04 | 1.10 | .19 | .39 |
| CO ₂ ----- | None | None | None | .19 | None | 1.35 | .23 |
| SO ₃ ----- | 7.45 | 2.00 | None | .13 | .04 | 1.04 | None |
| S----- | None | None | | | None | None | .13 |
| FeS ₂ ----- | | | 4.62 | 4.97 | | | |
| Fe (calculated)----- | 99.48 | 99.57 | 99.41 | 99.21 | 99.34 | 99.33 | 99.34 |
| Sp gr: Powder----- | 5.22 | 4.99 | 4.23 | 3.88 | 2.17 | 2.59 | 2.96 |
| Bulk (approx.)----- | 2.64 | 2.71 | 2.76 | 2.75 | 2.65 | 2.66 | 2.71 |
| | 2.25 | | 2.52 | | 2.58 | 2.59 | |

Spectrographic Determination of Minor Elements

[Analyst K. J. Murata]

| | | | | | | | |
|---------|-------|-------|------|--------|-------|-------|-------|
| Ag----- | | | | 0.0002 | | | |
| Mo----- | | | 0.01 | .01 | 0.009 | | 0.003 |
| Co----- | | | .01 | .003 | .002 | 0.001 | .002 |
| Ni----- | | | .007 | .003 | .003 | .003 | .002 |
| Be----- | | | Tr. | Tr. | Tr. | Tr. | Tr. |
| V----- | 0.006 | 0.007 | .01 | .008 | .01 | .01 | .01 |
| Cr----- | .006 | .007 | .01 | .02 | .01 | .01 | .01 |
| Zr----- | .01 | .02 | .008 | .01 | .01 | .01 | .01 |
| Sn----- | | | Tr. | Tr. | Tr. | | |
| Pb----- | | Tr. | .02 | Tr. | Tr. | Tr. | Tr. |
| B----- | | .0005 | | | | | |
| Ba----- | .04 | .04 | .02 | .05 | .03 | .05 | .03 |
| Sr----- | .02 | .04 | .01 | .02 | .01 | .06 | .03 |
| Y----- | | .003 | .002 | .003 | .003 | .002 | .003 |

1. Monzonite porphyry from kaolinite-alunite zone of alteration. Composite sample from outcrop in dry wash northwest of hole 77 and of rhyolite dike.
2. Monzonite porphyry from hydromica-pyrite zone. Churn-drill hole 9, composite of assay pulps 100-105 ft. and 120-125 ft.
3. Monzonite porphyry from hydromica-pyrite zone near copper ore zone. Churn-drill hole 11, composite of assay pulps 605-665 ft.
4. Monzonite porphyry from sericite-pyrite-chalcopryrite zone. Churn-drill hole I, composite of assay pulps 1,335-1,380 ft.
5. Monzonite porphyry from sericite-pyrite-chalcopryrite zone. Churn-drill hole 4, 350-450 ft.
6. Monzonite porphyry from marginal biotite zone. Churn-drill hole H, 825-875 ft.
7. Monzonite porphyry from marginal biotite zone. Churn-drill hole 7, 810-840 ft.

occupies a somewhat central position in the outcrop area (pl. 1). In the lowland north of Red Hill the red fades to the gray of the marginal biotite alteration (pl. 8). Along the south side of Red Hill the zone of hydromica-pyrite alteration is bordered by the San Manuel fault except to the southeast where the sericite-

pyrite-chalcopryrite rock emerges from beneath the conglomerate. Along the outcrop of the ore body, a diabase dike separates altered rock of the hydromica-pyrite type alteration from that of the sericite-pyrite-chalcopryrite type.

Drill holes through the Gila(?) conglomerate show that the most altered rock of the hydromica-pyrite type occurs in the area of the Houghton Group east of the San Manuel property. The greatest thickness, however, is along the southeast side of the San Manuel ore body.

Much information on the distribution of the hydromica-pyrite rock is available from the drill holes. The middle and western parts of the ore body are roughly tabular and dip southeast, as is shown by the cross sections (pls. 10-13). The footwall of this part of the ore body is characterized by hydromica-pyrite rock (pl. 3D).

Farther east the distribution is more complex, but in general the pyritic zone widens and swings around in a half circle to form the south boundary of the ore zone. The pyritic zone also occurs beneath the copper zone. The altered rock extends as far eastward and as far south of the eastern part of the ore body as these areas have been explored. Hole 94 on the southeast of the ore body passed through 1,540 feet of pyritic rock without reaching the bottom of the zone. Hole 100, south of the largest mass of ore, is in highly pyritic rock that assays only 0.08 percent copper from 835 to 2,500 feet.

The gradational zone from the copper ore to hydromica-pyritic rock extends over many feet. The boundary between the zones was drawn at 0.3 percent copper, although the cut-off used by the San Manuel Copper Corporation's engineers in calculating ore tonnage was 0.5 percent copper. Farther from the ore body the copper content decreases to only a few hundredths of a percent. Hole E, drilled on the southwest side of Red Hill not far from the present location of shaft 1, gives a good example of the relations. The geologic log is as follows:

Hole E; drill grid coordinates: 900.4 N., 600.6 W.

| | |
|---------------|--|
| Depth (feet): | |
| 0-162---- | Gila(?) conglomerate. |
| 162-185--- | Quartz monzonite, highly oxidized, much iron oxide. |
| 185-200--- | Quartz monzonite and monzonite porphyry. |
| 200-285--- | Quartz monzonite, bottom of oxide zone. (Average copper content from 162-285 ft. is 0.052 percent.) |
| 285-390--- | Quartz monzonite, much pyrite. |
| 390-405--- | Quartz monzonite and diabase, very strong pyrite. |
| 405-500--- | Quartz monzonite. Abundant pyrite. (Average copper content of sulfide zone from 285-500 ft. is 0.034 percent.) |

Hole N was also drilled mainly in the pyritic zone. Below the conglomerate, from 325 to 900 feet, is a mixed type of oxidized and slightly enriched rock that averages only 0.145 percent copper, and the unoxidized pyritic rock from 900 to 1,000 feet is still lower grade, averaging 0.045 percent copper. In both of these holes the amount of sulfide is much greater than in cuttings from the ore zone nearby.

The surface rocks of the hydromica-pyrite alteration range from dark red to moderate red and pink, depending on the amount of iron oxide stain. Iron oxide is concentrated at the surface, for rocks from test pits are lighter in color and many are mainly light gray, with red iron oxide along fractures. Small veins of nearly solid brownish-black iron oxide cut the rocks at places. Rock from below the zone of weathering ranges from light gray to medium gray or pale green.

The textures of both the monzonite porphyry and quartz monzonite are well preserved, and the two rocks usually can be easily distinguished even though both are highly altered. The preservation of the texture also makes it possible to determine the actual mineral changes which will now be discussed.

Commonly the rock contains a confusion of extremely fine-grained alteration products. The character is determined, however, by extreme pyritization, accompanied by the formation of hydromica and sericite. The hydrothermal minerals, approximately in order of abundance, are: pyrite, hydromica, sericite, kaolinite, quartz, allophane, chlorite, rutile, leucoxene, alunite, hydrobiotite, potash clay, halloysite, nontronite, dickite, montmorillonite, fluorite, and orthoclase (table 1).

Pyrite is abundantly disseminated throughout the altered rocks; less commonly, small veins of nearly solid pyrite cut the other minerals. No very precise data are available on the proportion of pyrite, but a composite assay of the Houghton Group's hole 2, from 1,025 to 1,050 feet, furnished by V. D. Perry, shows a calculated pyrite content of more than 20 percent. Samples from the ore zone in San Manuel property have been computed as containing as much as 5.5 percent pyrite, and it is evident from inspection of drill cuttings that the sulfide content of the pyritic zone is much higher than that of the ore zone. Probably an estimate of 10 percent pyrite would be about correct for the hydromica-pyrite zone as a whole.

The most abundant hydrothermal mineral except pyrite is hydromica. Oligoclase phenocrysts in the monzonite porphyry have altered to greenish or gray pseudomorphs that consist mainly of very fine-grained hydromica with lesser amounts of sericite, kaolinite, and allophane. Locally the hydromica may be relatively coarse grained (pl. 3D). Flakes of sericite often lie in a mat of hydromica, and the sericite grains have

sharp, straight edges which suggest that they have developed in the clay mineral rather than the hydromica in the sericite. In a few thin sections sericite clearly cuts across the clay minerals, leaving no doubt that it is, at least in part, later in age. Hydromica also cuts other clay minerals in the same manner. In some thin sections oligoclase has been altered to kaolinite, with oriented blades of alunite (pl. 2D), and kaolinite pseudomorphs after feldspar were observed partly replaced by veinlets of potash clay. Quartz is always abundant, but it is mostly primary, although original grains have recrystallized to aggregates in some rocks. Quartz veinlets occur in a few specimens, and some may be replacement. In general, however, this stage of alteration, in common with the other stages at San Manuel, is characterized by the scarcity of silicification.

Biotite has largely disappeared during the alteration. A few thin sections (8 of 27) show it altered to chlorite (delessite and penninite) and to a bleached brownish-green mica, probably hydrobiotite, with the usual clusters of rutile grains. More commonly, biotite has been completely bleached to form colorless sericite or hydromica. In many sections clusters of rutile grains are the principal evidence of the former existence of biotite, the alteration products having recrystallized to such an extent that the outlines of the phenocrysts have been largely destroyed.

Alunite is not common in rocks of hydromica-pyrite alteration but is conspicuous in a few thin sections, possibly representing a local access of the alunite-forming solutions. A particularly good example of clay-alunite alteration occurs in a fragment from a depth of 540 feet in hole C. The feldspar phenocrysts of the monzonite porphyry have altered to a very fine-grained mat that varies from a sericite-hydromica aggregate to relatively coarse blades of alunite in fine-grained dickite. Sericite flakes are clearly later than dickite, alunite, and hydromica. Minute quartz-pyrite veinlets partly altered to hematite cut the section, and small amounts of fluorite and barite were noted, mainly in late veinlets and microvugs; also a few grains of zunyite later than sericite but earlier than fluorite.

Quite significant is the outcrop high on the north slope of Red Hill of a dense monzonite porphyry dike that still contains unaltered pyrite which doubtless has been protected from supergene solution by the very dense character of the rock. This dike appears to represent an occurrence of kaolinite-alunite alteration within the hydromica-pyrite zone. The presence of much unweathered pyrite in this rock furnishes strong evidence of the hydrothermal origin of at least part of the kaolinite and alunite. In thin section feldspar proves to be completely altered to pseudomorphs consisting of coarse lath-shaped crystals of alunite (pl. 2B),

isotropic allophane, and dickite. A little sericite occurs in a veinlet cutting the clay minerals, and small crystals that were originally feldspar in the groundmass are altered to pseudomorphs of halloysite.

In the more severely altered rock of the hydromica-pyrite zone altered phenocrysts contain minute vugs, indicating considerable leaching without corresponding precipitation from the hydrothermal solution.

Thin sections of rocks from the Houghton Group drilling appear to justify the statement that where type 2 alteration was complete only quartz and a little residual orthoclase of the primary minerals remain, and the secondary minerals consist of pyrite, hydromica, kaolinite, and leucoxene. More complex mineral assemblages are characteristic of the intermediate development of this stage.

As in the kaolinite-alunite type of alteration the order of formation of the various fine-grained hydrothermal minerals is difficult to establish, but certain general changes are evident. The oligoclase phenocrysts alter at an early stage to pseudomorphs consisting of hydromica, kaolinite, sericite, alunite, and, less commonly, other minerals. Biotite alters at an early stage to a light brown or green mica (hydrobiotite and nontronite), chlorite, and rutile. With increasing alteration the iron is dissolved, and the biotite becomes muscovite or hydromica. Orthoclase and quartz of the groundmass resist change, but eventually the orthoclase alters to allophane, kaolinite, halloysite, sericite, and other related minerals. A few clearly late veinlets contain pyrite, quartz, less commonly sericite and hydromica, and rarely adularia.

The chemical composition of altered monzonite porphyry of the hydromica-pyrite type is shown by two analyses, one of a composite sample from hole 9, and the other of a sample from hole 11 (table 2). That from hole 9 was taken in the zone of oxidation from 100 to 105 and 120 to 125 feet. The pulp used for assay was also used for the rock analysis. Similarly from hole 11 the composite included the assay samples of sulfide-bearing rock from 605 to 665 feet. The analyses show a close correspondence in the amounts of some constituents and radical differences in others. The differences are largely explained by two facts. One sample is from the iron oxide zone, the other from the sulfide zone; also hole 11 is very close to the copper zone, whereas hole 9 is in the midst of a large area of hydromica-pyrite rock.

Silica, alumina, and lime contents are similar. The lime content is lowered with the alteration of the plagioclase feldspar. The content of magnesia is low in the sample from hole 9 but fairly high in the sample from hole 11. No good explanation is known. The potash content of the sample from hole 9 is moderate, as would be expected in the hydromica rock. The higher

potash in hole 11 indicates more hydromica, and probably some sericite, as was observed in thin sections of drill cuttings. The presence of 2 percent sulfate in rock from hole 9 suggests the presence of alunite, which was also seen in some thin sections of samples of this type of alteration. If all sulfate is calculated as alunite, the amount would be 5.2 percent and the remaining potash would form about 14 percent hydromica. Available alumina indicates about 22 percent kaolinite in hole 9 and only 4.3 percent in hole 11 where more potash is present.

Some data on the chemical composition of the quartz monzonite are shown in table 3. The presence in sample 1 of 2.88 percent FeS₂ indicates considerable impregnation with pyrite, but the amount of each of the bases indicates no extreme alteration. In sample 2 the very small amounts of lime and soda suggest the nearly complete alteration of the plagioclase feldspar, and a fairly high potassium content is indicative of the characteristic development of hydromica and lesser amounts of sericite.

TABLE 3.—Analyses of samples of altered quartz monzonite

| | 1 | 2 | 3 | 4 |
|--------------------------------------|-------|-------|-----------|-------|
| SiO ₂ ----- | 63.06 | 67.8 | 69.5 | 68.38 |
| Al ₂ O ₃ ----- | 14.44 | 12.5 | 11.9 | 12.89 |
| Fe ₂ O ₃ ----- | 6.57 | 7.6 | (FeO) 4.3 | 4.45 |
| MgO----- | 1.41 | 2.39 | 3.28 | 2.73 |
| CaO----- | 1.49 | .4 | .3 | 1.28 |
| Na ₂ O----- | 2.09 | .08 | .66 | .66 |
| K ₂ O----- | 3.59 | 3.46 | 3.37 | 4.12 |
| H ₂ O+----- | 1.83 | | | |
| H ₂ O----- | .30 | | | |
| TiO ₂ ----- | .96 | | | |
| P ₂ O ₅ ----- | .32 | | | |
| CO ₂ ----- | None | | | |
| SO ₃ ----- | .65 | | | |
| FeS ₂ ----- | 2.88 | | | |
| MnO----- | .04 | | | |
| CuO----- | .034 | | | |
| Cu----- | | .08 | .36 | .80 |
| | 99.66 | 94.31 | 93.67 | 95.26 |

1. Relatively unaltered quartz monzonite from hydromica-pyrite alteration (type 2). Hole 67. M. Fleischer, analyst.
2. Highly altered quartz monzonite from type 2 alteration. Hole 9 at 700 to 730 ft. Analysis by U. S. Bureau of Mines.
3. Quartz monzonite from sericite-pyrite-chalcopyrite alteration (type 3) at gradation to type 2. Hole 10 at 1,355 to 1,395 ft. Analysis by U. S. Bureau of Mines.
4. Quartz monzonite from type 3 alteration. Hole 15 at 1,745 to 1,810 ft. Analysis by U. S. Bureau of Mines.

The higher content of magnesia in sample 3 is unexplained. The analyses were made from the pulp of drill samples, and fragments for thin-section study are not available from this part of the hole. A higher content of chlorite could account for the magnesia because 7 of 18 thin sections of monzonite porphyry from the pyrite-hydromica zone contain chlorite.

**SERICITE-PYRITE-CHALCOPYRITE ALTERATION
(TYPE 3)**

The areal relation of the sericite-pyrite-chalcopyrite alteration to the other types is fairly simple in the western part of the San Manuel copper deposit where the hydromica-pyrite type forms the footwall and the marginal biotite type the hanging wall of a tabular zone of ore that dips approximately 50° to the southeast (pls. 10-13). To the east, the relations are more complex, and the hydromica-pyrite rock forms a zone that curves around the east end of the known ore zone and forms the south boundary. In the broad eastern zone the ore through part of its extent is divided into upper and lower bodies by several hundred feet of lean rock (pl. 9*F*, *L*).

The surface exposure of the copper-bearing rock is very limited in relation to the size of the ore body. In the main outcrop area of the ore zone, the ore-bearing rock is sharply set off from the red surface rock of type 2 by a narrow diabase dike (pl. 1). On the south side of the dike the mineralized rock is a reddish brown subdued by coatings of chrysocolla on even the most minute fracture surface of the better mineralized rock. There is a sharp contrast between the moderate red color of the weathered hydromica-pyrite rock and the subdued reddish brown of the weathered copper-bearing rock. In the brilliant sunshine of the desert the effect is actually that of bright red in contrast to purple, essentially like that emphasized by Locke (1926, p. 114).

In and near the ore zone are a few shear zones with a concentration of chrysocolla that makes them more conspicuous than the adjacent rock. The largest shear zone is north of hole 2 and the diabase dike, and roughly parallels the outcrop of a rhyolite dike. There a black, dense, siliceous material grades into a narrow vein of chrysocolla.

The copper-bearing rock at depth below the zone of oxidation is of varying shades of gray, which accentuate the difference between quartz monzonite and monzonite porphyry. The coarse quartz of the granitic rock usually escapes alteration, and the rock remains a mottled dark and light gray. The monzonite porphyry is an even light gray because its phenocrysts have been altered to sericite and to various minerals of the clay group. Sulfide is disseminated throughout but in most rock does not comprise more than 5 percent of the total.

Because of the economic importance of the ore zone, it has been studied in detail; the petrography of the hydrothermally altered rock comprising this zone is based on a microscopic study of more than 80 thin sections nearly equally divided between monzonite porphyry and quartz monzonite, and with a few of diabase. Most of the thin sections were made from rock chips recovered from the churn-drill cuttings.

The mineral composition of the ore rock varies from fairly simple in the most intensely mineralized specimens to very complex in the less advanced stages of alteration of the original rock (table 1).

Granitic rocks that have undergone the most intense alteration are characterized by a fine-grained mat of sericite crystals that completely replaced feldspar and to some extent replaced quartz. (See pl. 2*E*.) It also contains chalcopyrite, pyrite, hydromica, allophane, and small amounts of rutile. The former presence of biotite grains is now revealed by clusters of rutile grains. Minute vugs are lined with sericite and pyrite crystals. The groundmass of the monzonite porphyry is entirely altered to a mosaic of quartz grains, fine-grained sericite, and lesser amounts of other alteration products. Minute grains of chalcopyrite (pl. 2*E*) are disseminated throughout the rock.

Rocks that have undergone less intense alteration have, in addition to the foregoing minerals, some or all of these constituents: potash clay, kaolinite, hydrobiotite, chlorite, adularia, leucoxene, and less commonly zoisite, calcite, nontronite, beidellite, barite, and orthoclase (table 1). In both monzonite porphyry and quartz monzonite sericite is largely confined to plagioclase grains. It also forms pseudomorphs after biotite grains. In some thin sections sericite flakes occur in a matrix of kaolinite or fine-grained hydromica, where the sericite seemingly has replaced kaolinite or hydromica; larger sericite flakes or blades cut across the minute flakes of the other mineral in the matrix. Some veinlets contain chalcopyrite, pyrite, barite, and adularia, in addition to sericite. Adjacent to such veinlets sericite has often recrystallized to much coarser material. In these occurrences a close relationship exists among quartz, sericite, pyrite and chalcopyrite.

Careful examination of sericite areas often shows that there is much of a fine, flaky mineral of lower birefringence and slightly lower index than sericite. Much of it is undoubtedly hydromica, although in some extremely fine-grained aggregates it is impossible to distinguish between the two when the sericite flakes are less than 0.03 millimeters in thickness. Where the grains are larger the slightly greater index of sericite makes the distinction possible. The occurrence of hydromica is essentially like that of sericite except that it does not occur in the veinlets, evidently being an earlier mineral, because veinlets containing sericite clearly cut across the hydromica.

In 16 of 79 tabulated thin sections a fine mat of flakes with a birefringence between those of hydromica and kaolinite occurs with the other minerals in former feldspar areas. This corresponds to what has been termed potash clay.

In a few drill holes of the Houghton Group a greenish-gray rock was cut in the ore zone. Thin sections of it reveal a very fine-grained flaky mineral aggregate. X-ray determinations prove kaolinite to be an important constituent, and microscopic data show that both chlorite and sericite are present. The kaolinite and sericite are so intimately intergrown with green chlorite that the aggregate seems superficially to be mainly chlorite, and possibly is, in part, antigorite. Small amounts of kaolinite of normal appearance have replaced plagioclase grains and because it occurs in rock from the sulfide zone, its hydrothermal origin is evident. Sericite and hydromica are normally associated with kaolinite, and their relations with it suggest that both are later than the kaolinite.

In a few thin sections calcite occurs as late veins; it also occurs as irregular patches in some specimens. The evidence indicates that it is later than all other hydrothermal minerals, including pyrite and chalcoppyrite.

Biotite has been largely destroyed during hydrothermal alteration in the sericite-pyrite-chalcoppyrite zone, but locally it seems to have survived even though the rock is highly altered otherwise. In these examples it usually shows some bleaching and recrystallization to aggregates. More often it has altered to a pale brown or green, and has moderate birefringence. This mineral corresponds to hydrobiotite and was recognized in 36 thin sections of copper-bearing rock.

Sales and Meyer (1950, p. 270) have noted recently that biotite is stable in the kaolinite subzone at Butte. No evidence of secondary biotite has been found in the kaolinite, hydromica, or sericite zones at San Manuel, but some may have formed in the marginal biotite zone, as indicated later.

Chlorite was recognized in 39 out of 79 thin sections of quartz monzonite and monzonite porphyry from the copper zone. It often forms partial pseudomorphs after biotite and less commonly occurs as a replacement in former feldspar areas. Chlorite also occurs as spherulitic aggregates in veinlets containing quartz, sulfides, and sericite.

Allophane in small amounts occurs in many thin sections where it clouds the other minerals and causes them to appear to have a high relief. Quartz often contain minute inclusions of allophane and orthoclase that resist alteration to sericite; however, hydromica may be clouded with allophane which gives it a brownish appearance in transmitted light. There is no doubt that part of the allophane is hydrothermal, because it is found at depth in sulfide ore that has not been affected by oxidation.

Epidote and clinozoisite occur in some thin sections

of rocks from the copper zone, and a few other minerals including halloysite, beidellite, dickite, and montmorillonite were recognized, but they are not abundant enough to be significant.

The chemical composition of two composite samples of drill cuttings from the ore zone is shown by analyses 4 and 5 of table 2. These analyses are characterized by a fairly normal silica content, which confirms the fact that silification was not a very important process accompanying the introduction of the ore. Average silica in 69 composite analyses, mainly of ore-bearing rock, is 68.9 percent for quartz monzonite and 64.1 percent for monzonite porphyry. The ore excavated from shaft 2 has a moderate number of quartz veinlets that contain small amounts of chalcoppyrite, pyrite, and molybdenite. Veinlets cross earlier veinlets, furnishing evidence of repeated fracturing and introduction of quartz and ore minerals. Available evidence indicates that the amount of introduced silica approximates that removed during earlier alteration, but locally there was doubtless an increase in silica.

The analyses show a low lime content, as is to be expected because of the destruction of plagioclase by sericitic action and other processes of alteration. Lime in 52 composite analyses of ore-bearing quartz monzonite averages 0.4 percent, and 26 composites of ore-bearing porphyry average 0.43 percent lime. The importance of sericite is shown by the fairly high amount of potash in rock facies of various degrees of alteration. The metallic copper content is 0.74 and 0.78 percent in the two samples, and calculated pyrite is 4.67 and 4.97 percent.

A calculated mineral analysis of a sample from hole 1 shows 3.2 percent chlorite, about 20 percent sericite, and nearly 12 percent orthoclase; (necessary water was allotted to magnesia and the remainder to potash). The free silica indicated is 37 percent. For the sample from hole 4 similar results are: chlorite 3.7 percent, sericite 19.4 percent, orthoclase 17.7 percent, and quartz 29 percent. Only the content of albite is difficult to explain. The percentages are 16.2 in hole 1 and 19.7 in hole 4, and these seem high in view of the visible minerals. Figure 5 gives a comparison of the approximate calculated composition of the monzonite porphyry of the copper zone with rock that is both more and less altered. Part of the soda is doubtless in the orthoclase; so, the actual percentage of orthoclase is greater than that given above, and the calculated percentage of albite correspondingly lower. Some soda may also be combined with sericite.

Partial analyses of quartz monzonite listed in table 3 indicate that the chemical character of the quartz monzonite of the copper zone is much like that of the monzonite porphyry. The magnesia content is fairly

high, suggesting the presence of somewhat more chlorite, the only abundant magnesia-bearing mineral recognized in thin sections of the ore zone.

MARGINAL BIOTITE ALTERATION (TYPE 4)

A marginal biotite type of alteration is revealed wherever the rocks are exposed or cut by drill holes away from the principal area of alteration. Some of the rock may appear unaltered in hand specimen, but thin sections invariably show a confusion of alteration products. This type of alteration forms the hanging wall of the ore zone in the western part. North of Red Hill a facies of this stage of alteration characterized by epidote-zoisite minerals forms a large part of the area between San Manuel and the St. Anthony mine.

For more than a mile south of the ore deposit the older rocks are overlain by a thick blanket of conglomerate. About 2 miles southwest along State Highway 77 is an area with the same assemblage of older rocks (fig. 3), and there the porphyry shows essentially the same marginal-biotite type of alteration as that in the hanging wall of the ore body.

Most of the rock examined for this stage of alteration is monzonite porphyry. This is due to the fact that the porphyry is predominant in the upper part of the area of the ore body and also that the characteristics were more evident in the drill cuttings of the porphyry. The description of marginal biotite alteration will, therefore, be based mainly on the monzonite porphyry, with some particular references to the quartz monzonite.

The porphyry of this marginal biotite zone is usually medium to dark gray, with light-gray phenocrysts. This varies to a weak green where chlorite is more conspicuous or to a pinkish cast where oxidation has been effective. Black spots, often glistening, are present whenever biotite has escaped much alteration. The rock then appears comparatively fresh, but all thin sections have shown that alteration is extensive. Nevertheless, the original character of the porphyry may be inferred from this rock, and this has been done in deriving the description of the monzonite porphyry. In general the alteration minerals reflect the composition of the primary minerals, and chemical change has been relatively slight. This is to be expected in what is essentially a fringe zone of alteration. Altogether 57 thin sections were made of specimens of this type from widely scattered outcrops and many drill holes.

The primary minerals are fairly well preserved in some sections and consist of oligoclase (Ab_{70}, An_{30}), orthoclase, quartz, biotite, apatite, and zircon. The hydrothermal minerals include about the same species that are found in other zones but in different proportions and the marginal biotite rock has many mineral

species in most of the specimens, thus making every thin section a very complex assemblage (table 1). The hydrothermal minerals roughly in order of abundance are: hydromica, chlorite, secondary biotite, hydrobiotite, sericite, calcite, quartz, kaolinite, allophane, rutile, leucoxene, and potash clay. Epidote and clinzoisite are abundant in a few thin sections but absent in most. The clay minerals halloysite, beidellite, and dickite are not known to occur in this zone nor does alunite, a conspicuous mineral of kaolinite-alunite alteration. Pyrite is common in unoxidized specimens from the hanging-wall area, but is not abundant. The abundant primary minerals show a well-defined susceptibility to alteration in the following order: biotite, plagioclase, orthoclase.

The most distinctive feature of rocks of marginal biotite alteration is the abundance of biotite and the many products that result from its breakdown during hydrothermal alteration (pl. 3A-C). Biotite occurs in the monzonite porphyry as small euhedral phenocrysts that are as much as 4 mm in diameter and as abundant small grains in the groundmass of the porphyry. Biotite is more intensely altered than the feldspars and the first step in alteration is a recrystallization of the biotite phenocrysts into aggregates of biotite grains within the outline of the original grain (pl. 3A). Generally the recrystallization is accompanied by some bleaching to a lighter brown.

In places the bleaching is pronounced and may affect grains that have not recrystallized; the mineral has less birefringence, thus corresponding closely to hydrobiotite. During recrystallization titanium in the biotite crystallized as minute euhedral to subhedral grains of rutile (pl. 2F) and often leucoxene. Leucoxene also occurs as an alteration product of ilmenite. The amount of recrystallization and bleaching varies greatly even in a single thin section, and in many sections there is considerable alteration to a light green mica having somewhat lower birefringence than biotite. From the nature of its occurrence there seems little doubt that it is lower in iron content and higher in magnesium and hydroxide, because its formation is accompanied by bleaching and the formation of hydrous minerals in the feldspars. The bleaching of biotite proceeds so far in some crystals that a perfect pseudomorph of colorless mica is formed. This may be termed secondary muscovite, or sericite, if one considers sericite as a secondary mica rather than a secondary mica with a shredlike structure. In other examples the pseudomorphs consist of a colorless mica (hydromica) with a low birefringence usually somewhat variable throughout an individual grain. The alteration of biotite does not appear to have gone far enough to develop kaolinite in the pseudomorphs after biotite.

In other specimens, or even within a single specimen, biotite has also been altered to chlorite, and excellent pseudomorphs of chlorite after biotite are common. Delessite forms an early variety, and penninite is usually later. An exceptional occurrence is that on the prominent hill between Red Hill and Tiger where epidote and clinozoisite form clusters of grains within chlorite pseudomorphs after biotite (pl. 3B). An unusual feature of the alteration of some biotite grains is the alteration of certain layers to chlorite, with alternating layers replaced by calcite (pl. 3C). Some grains show layers of calcite, chlorite, and bleached biotite. It is characteristic of the biotite lenses to display distortion, suggesting perhaps that the crystallization of calcite exerted some force in making way for itself.

Some marginal biotite rocks in the hanging wall of of the ore body have such an abundance of fine-grained biotite in the matrix as to give the impression that biotite has been introduced as it was in some facies of the porphyry at Bingham, Utah, and Ely, Nev. (Schwartz, 1947, p. 322). Among the best examples of disseminated biotite was a series of samples from 755 to 1,270 feet in hole 45. The original biotite grains are frayed around the edges, and minute grains are well distributed throughout the rock. The fact that the four samples from which the thin sections were taken averaged 0.56 percent copper indicates fairly intense hydrothermal action. In a few thin sections the fine-grained biotite is well disseminated throughout the section in a manner that suggests partial rearrangement and redistribution of the biotite. The fact that biotite and hydrobiotite flakes were observed embedded in kaolinite pseudomorphs after plagioclase seems particularly to bear out this possibility. Some of the biotite may be deuteric, but there is no doubt that recrystallization of biotite to aggregates and alteration to hydrobiotite is hydrothermal. Identical changes have been observed in other copper-bearing porphyries. Determination of the exact extent of the changes in biotite, particularly its possible formation during hydrothermal alteration, is complicated by the fact that the monzonite porphyry has not been found in an unaltered state, and the exact nature of the primary biotite is therefore in some doubt.

T. S. Lovering (personal communication) examined two thin sections from this zone and commented on biotite as follows:

The behavior of biotite in the marginal biotite zone is instructive. It is more intensely altered than the feldspars and shows the following progressive changes: 1. bleaching (to a hydrobiotite); 2. hydrobiotite to delessite and rutile; 3. delessite to penninite; 4. penninite and delessite to hydromica and sericite. The first stages reflect the preferential leaching of iron. The chlorite suggests a stage where potash was also being removed, perhaps

synchronous with the allopahanization of orthoclase, and the fourth stage indicates a renewed supply of potash in the altering solutions that is in harmony with the changes seen in the alteration of the feldspars.

The oligoclase phenocrysts of the monzonite porphyry all show alteration. The first stage involves the formation of much extremely fine-grained allopahane that gives the feldspar a brownish color in transmitted light. A common product is sericite, often more abundant in certain zones of the crystal. Where it has been little altered, sericite is often oriented along crystallographic planes, but in thin sections where it is abundant it cuts earlier alteration products as veinlets.

Some specimens contain much kaolinite and potash clay associated with hydromica; and the clouding of feldspar, especially orthoclase, by allopahane is common, and in fact, seems characteristic of the early stage of this type of alteration. Orthoclase is a groundmass mineral and, in contrast to plagioclase of the phenocrysts, resists extensive alteration in this zone. Potash clay is more common than in other zones, indicating that removal of potash was incomplete. In general it was found that sericite was distinctly subordinate in this zone and kaolinite and potash clay prevalent although not abundant. This, with the relative importance of calcite, emphasizes the subordinate role of potash in the marginal biotite alteration.

Chlorite is a common alteration product of feldspar, and perhaps some of the iron released during the destruction of biotite is deposited in the feldspar. In some thin sections two varieties, delessite and antigorite, were recognized. The replacement of feldspar by chlorite emphasizes the fact that the solutions did not simply alter material in place, but removed some of the bases, particularly calcium and sodium, and introduced iron, magnesium, and especially potassium where sericite was formed.

Calcite is common in this zone. It occurs in biotite as an alteration product of oligoclase and as veinlets. Inasmuch as most calcium has been removed from the zones of more intense alteration, it is probable that the introduced calcium of the marginal zone was actually derived from the other zones by solutions that moved outward.

Introduced quartz is not conspicuous in this zone. Small amounts of recrystallized quartz occur in a few thin sections and in veinlets. The total secondary quartz is small and probably represents little addition of silica. Pyrite and chalcopryrite are associated with the vein quartz near the ore zone. Minute veinlets of quartz and the adjacent rock contain sericite, quartz, orthoclase, barite, pyrite, and chalcopryrite.

Generally, the fine-grained quartz-orthoclase mosaic of the groundmass has been little altered in the marginal

biotite zone. Magnetite and probably magnetite-ilmenite remain in a few of the rocks, whereas in the zones of more intense alteration magnetite has usually been so thoroughly destroyed that no hint remains of its original occurrence. In some specimens part of the magnetite has been altered to martite (pl. 3*F*) and is presumably supergene because alteration has occurred where pyrite has been oxidized.

The chemical composition of two composite samples from drill holes in the marginal biotitic zone of alteration is shown by analyses 6 and 7 of table 2. These analyses are believed to represent only moderate changes from the original composition of the porphyry, although the amount of combined water indicates some change as does the amount of carbon dioxide and sulfur trioxide in analysis 6. Lime is very low, considering the fact that the small amount of fresh plagioclase found in some thin sections proves to be oligoclase of medium composition. The amount of soda in the analyses strongly indicates that oligoclase breaks down readily to liberate albite, as suggested by Gilluly at Ayo (Gilluly, 1946, p. 31). Calculation of magnesia as biotite, allotting an equal weight of ferrous iron, gives an indicated biotite content of 15 percent in analysis 6, and 11 percent in analysis 7. At least a small part of the material calculated as biotite actually occurs as chlorite, as is evident from the microscopic work. The amount of combined water and the alumina content indicate an appreciable amount of kaolinite and allied clay minerals.

A significant feature of the hanging-wall zone is persistence of a small copper content for hundreds of feet above the sericite-pyrite-chalcopryrite zone. In hole 15 the base of the Gila(?) conglomerate is at a depth of 365 feet. Assays are available, beginning at 490 feet and continuing in low grade, weakly altered rock to 1,300 feet; the average copper content is 0.328 percent. Panned concentrates were examined, beginning at 695 feet. As would be expected, several had very little, if any, copper mineral, but a few show stray grains of pyrite, chalcopryrite, and chalcocite, and have rutile as the abundant mineral in the concentrates. Copper content is low and fairly consistent from 695 to 1,160 feet; then it becomes somewhat erratic, having an occasional assay as high as 0.5 percent copper. There is a moderate amount of chalcocite partly replacing pyrite and chalcopryrite. From 920 down to 1,265 feet is a zone in which there is very little sulfide, and the concentrates are red with rutile. At 1,265 feet sulfide appears, including chalcocite and minor covellite and bornite. At 1,300 feet the assays show a higher copper content, and sulfide becomes distinctly more abundant in the concentrates. Other examples of long sections of low-grade hanging-wall rock are shown in plates 10-17.

CHEMICAL CHANGES

The precise determination of gains and losses during hydrothermal alteration of the rocks of the San Manuel deposit is impossible because most of the specimens were drill-sample pulps, and unaltered rocks are not available for the monzonite porphyry. Some data on porosity calculated from specific gravity indicate that porosity is not high in the altered rocks.

Lovering (1948, p. 5), gives bulk and powder specific gravity determinations for three specimens:

| | Bulk | Powder | Percent of porosity |
|--|-------|--------|---------------------|
| Quartz monzonite, surface Red Hill ---- (weathered hydromica-pyrite rock) | 2.454 | 2.704 | 9.2 |
| Monzonite porphyry, hole 73-735 ft. (oxidized ore) | 2.475 | 2.593 | 4.5 |
| Monzonite porphyry, hole 15-1,900 ft. . . (sulfide ore) | 2.544 | 2.648 | 3.9 |

The San Manuel Copper Corporation made 20 specific gravity determinations of rock specimens from hole 59, drilled with a rotary machine (table 6, page 62). Three determinations of sulfide ore in monzonite porphyry ranged from 2.572 to 2.711 and gave an average specific gravity in bulk, of 2.634. Three determinations of ore in weathered quartz monzonite averaged 2.658; four determinations of oxidized ore in monzonite porphyry ranged from 2.516 to 2.583.

The calculated porosities for some of the rocks whose analyses are shown in table 2 are as follows: no. 1, kaolinite-alunite zone, 14.8 percent; no. 3, pyrite-hydromica zone, 8.7 percent; no. 5, sericite-pyrite-chalcopryrite zone, 2.6 percent; and no. 6, marginal biotite zone, 2.6 percent. The fact that porosities are not high except in the kaolinite-alunite rock indicates that gains and losses shown by the analyses are a fair indication of the chemical changes.

In the early stages of the work the Bureau of Mines laboratory at Reno made six determinations of soda in composite samples from holes 9, 10, 11, and 15. Those from holes 9 and 11 are from the hydromica-pyrite zone, and those from 10 and 15 from the sericite-pyrite-chalcopryrite zone. The amounts of soda varied from 0.08 to 0.83 percent, thus verifying the low soda content indicated by the complete analyses of table 2. The lime content of the same samples reaches a maximum of 1.23 percent.

Magnesia largely remains in the zones of less intense alteration and is somewhat erratic in the sericite-pyrite-chalcopryrite and hydromica-pyrite zones. It is high in one of the complete analyses (no. 3) and in a composite sample from hole 11, analyzed by the Bureau of Mines, which ran 6.88 percent. Other determinations from holes 9, 10, 11, and 15 ranged from 1.24 to 3.28 percent. In contrast, magnesia is practically absent from the kaolinite-alunite zone.

Potash falls to relatively low percentages in the kaolinite-alunite and hydromica-pyrite zones in spite of the presence of alunite and hydromica. The relatively high potash content in the copper zone is in accord with the extensive replacement of the rock minerals by sericite. Accompanying the low-content potash of the kaolinite-alunite zone is a high combined water content corresponding to the high degree of hydration of the clay minerals in comparison with such minerals as sericite, hydromica, hydrobiotite, chlorite, epidote, and clinozoisite. Determinations of potash in several composite samples from holes 9, 10, 11, and 15 range from 2.99 to 4.12 percent.

The percentage of silica does not show a radical change except in the kaolinite-alunite zone where abundant alunite takes the place of silicates in the less completely altered rocks. It is significant that the percentage of silica of the ore zone approximates that of comparatively little-altered rock probably having less pore space. In analyses 4 and 5 of rock from the ore zone the silica content is higher than in analysis 6 and lower than in analysis 7, both from the less altered marginal zone.

The total iron calculated from the iron oxides and pyrite shows that the ore zone is not especially high in iron but that the hydromica-pyrite and kaolinite-alunite types of alteration have nearly double the percentage in the least altered rock from the marginal zone. A better indication of the total iron in the ore zone is furnished by a series of composite assays in which the total iron content was determined by the San Manuel Copper Corporation. An average of 16 composites showed 3.5 percent iron; the range was from 2 to 5.3 percent. The higher grade copper assays showed the lower iron content; this coincides with the observation that the amount of sulfide increases as the ore grades into pyritic rock. The sulfur content is also higher in the pyritic rock, as noted below. A selected series of composite samples of average grade ore (0.81 percent) gave an average total iron content of just less than 3 percent. The average iron content of the ore (type 3 alteration) probably averages about 3 percent. In hole 5, ore for a thickness of 535 feet averaged 3.13 percent iron. Potash and soda show a decrease from the marginal biotite type through hydromica-pyrite type and kaolinite-alunite type and then an abrupt rise corresponding to the extensive sericitization of the ore zone. The combined water content shows a large increase in kaolinite-alunite and hydromica-pyrite zones and then a big decrease in the ore zone which is not characterized by highly hydrous minerals.

The amount of sulfur in unoxidized rock in some degree indicates the amount of alteration. Data for

unoxidized rock from the kaolinite-alunite zone is not available, but the sulfur trioxide content of surface rock is 7.45 percent. An average of 38 sulfur determinations of composites from various holes shows 3.61 percent sulfur for the hydromica-pyrite zone. The range is from 1.8 to 9.7 percent. The average of 19 composite samples from the sericite-pyrite-chalcopyrite zone is 2.76 percent, with a range from 1.8 to 4.5 percent. Comparable data are not available for the marginal biotite zone, but microscopic examination shows that the sulfide content is low and decreases with distance from the ore zone. The sample from 810 to 840 feet in hole 7 contained only 0.13 percent sulfur.

SEQUENCE OF ALTERATION

The sequence of the complicated alteration is hard to determine and evidence is not always decisive. The simplest explanation would be that the four types of alteration form a sequence from the kaolinite-alunite zone to the marginal or fringe zone alteration. The principal difficulty with this explanation is that the sericite-pyrite-chalcopyrite rock exists only on the south side of the exposed part of the hydromica-pyrite zone. The relations between the zones in the eastern part of the ore body are not clear because of the heavy cover of conglomerate and the incomplete drilling of the area, but in the western part the diagrammatic relation between footwall (type 2), ore zone (type 3), and hanging wall (type 4) has been described.

Except along the south side, alteration types 1, 2, and 4 form a gradational series of decreasing intensity. The rock from the ore zone cut by shaft 2 shows many quartz-sericite-pyrite-molybdenite veinlets as much as an inch in width. These did not all form at one stage, because some veinlets cut across earlier veinlets. It would thus appear that the copper-bearing sericitic alteration is somewhat exceptional and is perhaps superimposed on the other types or zones along a structurally favorable area. Because of a lack of outcrops in the ore zone, except for one small area, the structural nature of the zone is uncertain, but its tabular form throughout the western part suggests a zone of fracturing. The irregular shape to the east may be caused by cross fracturing. The suggested relations may be indicated diagrammatically by types 1, 2, and 4 as being concentric zones, with type 3 cutting across the pyrite-hydromica and biotitic zones in accord with the evidence of the late introduction of much sericite (fig. 7).

Varying interpretations will doubtless be made of the preceding facts. The early phase of alteration was made clearly by solutions of low acid content that leached most of the rock constituents to some extent, particularly lime, soda, and magnesia. This period of early leaching was followed by one in which potash

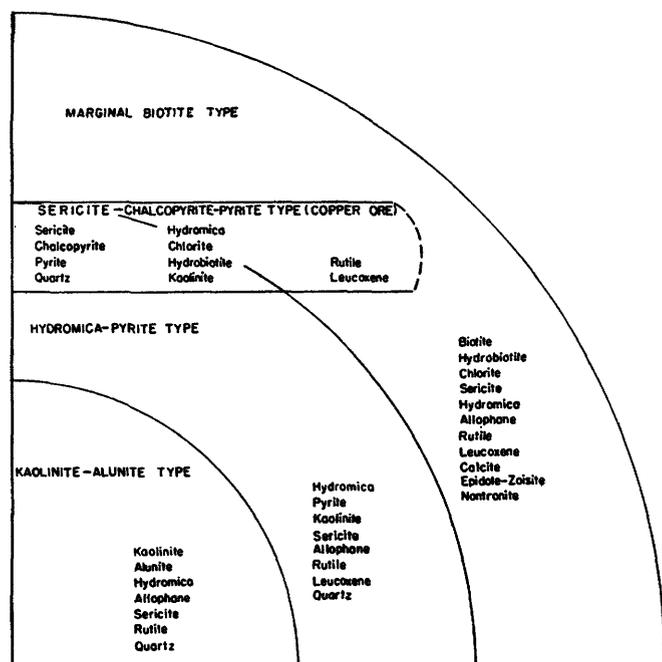


FIGURE 7.—Schematic diagram of possible relations of various types of alteration at San Manuel copper deposit

was added, forming hydromica and sericite and, in late veins, orthoclase and quartz. Iron and magnesia were progressively driven out. In the early stage iron was leached preferentially from the original biotite, leaving hydrobiotite and chlorite. As alteration progressed potash replaced the magnesia, resulting in pseudomorphs of muscovite after biotite.

The presence of late calcite veinlets in the fringe zone and locally in the ore probably represents precipitation of calcium leached from zones of intense alteration. Rare chlorite veinlets may also represent magnesia driven out of biotite at places where intense leaching was in progress.

According to this interpretation, the most intensely altered, or kaolinite-alunite, zone is the place where hydrothermal solutions permeated the rock most thoroughly and altered it almost beyond recognition. This small zone grades into the hydromica-pyrite type of alteration which is also intense, but the original character of the rock is easily distinguished. Its close relation to the preceding zone is indicated by the local presence of alunite, and by a similar assemblage of minor minerals. The pyritic zone at its outer edge grades into the marginal biotite zone, as is clearly shown in the outcrops between Red Hill and Tiger.

WEATHERING

The rocks now exposed in the San Manuel and adjacent areas are disintegrating with very little decomposition. Road cuts along the highway between Oracle

and San Manuel expose quartz monzonite that has partly broken down to a rubble, but examination reveals little decomposition. Feldspar retains its glassy luster, and biotite looks fresh. This is typical desert weathering.

In the area near the ore body where the rocks have been altered by hydrothermal solutions the rocks crumble even more readily, and more chemical decomposition has taken place in proportion to the extent that sulfides were present in the unweathered rock.

There is little difficulty in recognizing many of the changes that have gone on in the ore minerals during weathering. Pyrite has been altered to goethite and hematite. Goethite is colored red by the presence of some hematite. Less commonly jarosite has formed. The copper sulfides have altered to cuprite to some extent, but much of the copper in the oxide zone has combined with silica and has been deposited as chrysocolla along fractures in the rock. In general, the evidence suggests that the primary copper minerals were oxidized and that the copper then was dissolved and precipitated as chrysocolla along fractures.

Minerals believed to be developed by weathering in the San Manuel deposit and immediately adjacent area include: opal, cuprite, malaconite, hematite, goethite, psilomelane, calcite, malachite, azurite, chrysocolla, allophane, halloysite, and jarosite. It is probable that some kaolinite and other clay minerals were formed partly by weathering, but only kaolinite is abundant enough to be important.

MINERALOGY

Many of the minerals in the San Manuel area occur as extremely fine-grained alteration products that could be recognized only under the microscope. In the determination of the alteration minerals the writer followed the table prepared by Lovering (1949, fig. 12), using his values for optical constants and checking against descriptions in available textbooks on optical mineralogy. These determinations were verified by X-ray where it was possible to obtain reliable samples, and the optical and X-ray data were in close agreement. Comparison of the indices of refraction of minerals that are in contact was found particularly helpful. Many thin sections showed such fine-grained aggregates that an oil immersion lens was essential to the work. T. S. Lovering and Bronson Stringham examined several thin sections of altered rocks.

MINERALS AND THEIR OCCURRENCE

COPPER

Native copper [Cu] occurs in abundance in some of the panned concentrates from the San Manuel drill cuttings.

Generally, it is in the lower part of the supergene sulfide zone and does not occur at the surface but in one hole native copper was abundant at the top of the supergene sulfide zone where it probably originated by destruction of chalcocite. It is now partly oxidized to cuprite. Polished surfaces reveal some grains of chalcocite partly replaced by native copper along cracks and in rims around the grains (pls. 3E, 6C). In many concentrates the native copper occurs as flakes and small grains free from other minerals; their derivation is not evident but, in part, they may have been formed by direct precipitation from supergene copper-bearing solutions.

Native copper is conspicuous in some of the drill cuttings, but it is doubtful that it forms an important part of the copper content except in rare samples. The copper has a high specific gravity (8.8) and concentrates easily in panning, thus giving a false impression of its abundance.

MOLYBDENITE

Molybdenite [MoS₂] is widespread but occurs in very small amounts. Preliminary composites indicated an average content of 0.02 to 0.03 percent of molybdenum. The mineral is rarely seen in the rock fragments of drill cuttings but shows up in the concentrates as small flakes. Where visible in the rock, it is normally associated with small quartz veinlets as was clearly shown by the rock excavated from the ore zone in shaft 2. Molybdenite was not observed in the oxide zone, and as it occurs in such small amounts, its alteration products might easily escape detection in the complex of hydrothermal and oxidation products.

CHALCOCITE

Chalcocite [Cu₂S] is next to chalcopyrite in importance as a source of copper in the San Manuel deposit. It is believed to be exclusively of supergene origin because it does not occur, even in microscopic amounts, in the deeper hypogene part of the deposit. Small amounts of chalcocite may occur almost anywhere in the rocks for some distance beneath the Gila(?) conglomerate, and it occurs practically at the surface near the head of Cloudburst Wash canyon northwest of San Manuel. Most of the chalcocite, however, is in the upper part of the supergene sulfide zone which varies greatly in depth in different parts of the ore body (pl. 9). Commonly, chalcocite that has replaced pyrite shows a concentric structure (pl. 6D) which has been previously described in the ore from Globe (Schwartz, 1921, pp. 322-329).

SPHALERITE

Sphalerite [ZnS] was recognized in only one sample of mounted concentrates where it occurred with chalcopyrite and pyrite, apparently as a normal hypogene mineral. This rarity of sphalerite in the San Manuel

ore is significant because at the St. Anthony mine, less than a mile to the north, it is the most abundant sulfide mineral, and zinc-lead ore formed the major part of the production in recent years from this important mine, now closed.

GALENA

Galena [PbS] has not been observed in the San Manuel deposit but, like sphalerite, was an important ore mineral in the St. Anthony mine.

COVELLITE

Covellite [CuS] is a widespread but sparse mineral in the supergene sulfide ore but is not known as a hypogene mineral at San Manuel. It is most common as small blades and feathery aggregates replacing chalcocite (pl. 5C), and its even distribution in some grains suggests an origin by exsolution, as shown by Bateman and Lasky (1932, pp. 52-86) for the Kennecott ore.

BORNITE

Bornite [Cu₅FeS₄] is a very minor constituent of the San Manuel ore but is widespread, usually as minute amounts mainly in supergene sulfide ore, but it also occurs in hypogene ore in very small amounts.

The most common occurrence is as a faint halo varying to a distinct rim around remnants of chalcopyrite in supergene chalcocite. Locally, bornite has developed more extensively as a replacement of chalcopyrite (pl. 4D).

A very few grains of sulfide show crystallographic intergrowths of bornite and chalcopyrite (pl. 4E) that are probably a result of overheating the panned concentrates while drying them, for similar structures have been produced experimentally at temperatures around 475° C (Schwartz, 1931, p. 194). This was avoided in most of the drilling by drying with a steam table.

In some grains chalcopyrite and bornite are present in a relationship that gives little evidence of a disparity in age and in this occurrence are believed to be essentially contemporaneous and of hypogene origin. Other intergrowths suggest hypogene replacement of chalcopyrite by bornite (pl. 4F), but most replacements of chalcopyrite by bornite in this ore are supergene.

CHALCOPYRITE

Chalcopyrite [CuFeS] is the most abundant copper mineral at San Manuel and the only hypogene copper sulfide of importance. In the unaltered hypogene ore it is closely associated with pyrite with which it was formed contemporaneously or replaced to a minor extent (pl. 5A). Some late quartz veinlets contain pyrite and chalcopyrite; so no consistent age difference is shown. The chalcopyrite and sericite zones appear to coincide, suggesting that these minerals were contemporaneous.

In the hypogene ore, fully 80 percent of the chalcopyrite is finely disseminated throughout the altered quartz monzonite and monzonite porphyry (pl. 2E). Chalcopyrite also occurs in small quartz veinlets with pyrite, molybdenite, and, less commonly, other minerals.

Chalcopyrite has been partly replaced in the supergene sulfide zone by chalcocite (pl. 4B) and to a lesser extent by bornite and covellite. Also, chalcopyrite has been observed as a late replacement of bornite, but this is extremely rare. Veinlets of the supergene sulfides cut chalcopyrite as a network, and where replacement has been extensive, small rounded or irregular remnants of chalcopyrite remain. It has been replaced in preference to pyrite; so, chalcopyrite was commonly destroyed before pyrite was much altered. Chalcocite often replaced chalcopyrite directly, but also fairly common was replacement by bornite or covellite that in turn altered to chalcocite as the supergene process continued (pl. 5C). A latticelike replacement of blade-like crystals of covellite along the octahedral planes of chalcopyrite is fairly common and was observed in many stages of development (pl. 4C). Exceptional is a supergene replacement of pyrite by chalcopyrite (pl. 5B).

PYRITE

Pyrite [FeS_2] is by far the most abundant metallic mineral in the district. It is always an important constituent in the hypogene ore and is the only important sulfide in the footwall and some other areas of intense alteration. It normally occurs as individual grains or crystals thickly disseminated throughout the rock. Pyritohedrons and cubes modified by octahedrons were observed. In the ore and pyritic zones pyrite occurs with quartz in small veinlets. The high pyrite content of a few samples of drill cuttings indicate more substantial pyrite veins. Minute inclusions of chalcopyrite in pyrite are common in ore and low-grade pyritic rock.

In the oxide zone at San Manuel, red iron oxide pseudomorphs after pyrite cubes are frequently observed, especially in thin sections. Pyrite also occurs in various stages of replacement by goethite (pl. 6A, B).

The formation of pyrite was characteristic of at least two types of hydrothermal alteration. In the hydromica type it is the abundant associated hydrothermal mineral, and in the sericite-pyrite-chalcopyrite type of alteration (ore zone) pyrite is the most abundant sulfide.

QUARTZ

Quartz [SiO_2] occurs in most of the rocks of the district and has various forms. It is most conspicuous in the quartz monzonite, which is coarse grained and has

quartz grains as large as 5 millimeters in diameter. In the aplite, quartz forms a fine granular aggregate with orthoclase. In the monzonite porphyry it occurs with orthoclase as an extremely fine-grained mosaic and, rarely, as a few small phenocrysts.

Vein quartz is not abundant in the ore or other rocks of the area, but small quartz veinlets are common. Small vugs lined with quartz crystals have been observed in some of the outcrops of oxide ore and in some of the rocks most intensely altered by hydrothermal solutions.

In the intensely altered rocks some of the quartz has a wavy extinction, and inclusions of quartz of different extinction occur within the sheaflike grains. The inclusions are probably primary and the enclosing areas hydrothermal in origin. Some original grains have recrystallized during hydrothermal alteration to a mosaic of new grains within the area of the primary grain. A few quartz grains display ragged edges as if attacked and somewhat replaced by sericite. Fluid inclusions are common in much of the quartz.

One good example of silicification occurs along a shear zone about 100 feet west of hole 77. Here the vein material is a dense, black silica with a brecciated texture. The inner part of the vein grades into chrysocolla, and the material along the vein is the best surface-showing of oxidized copper ore in the area.

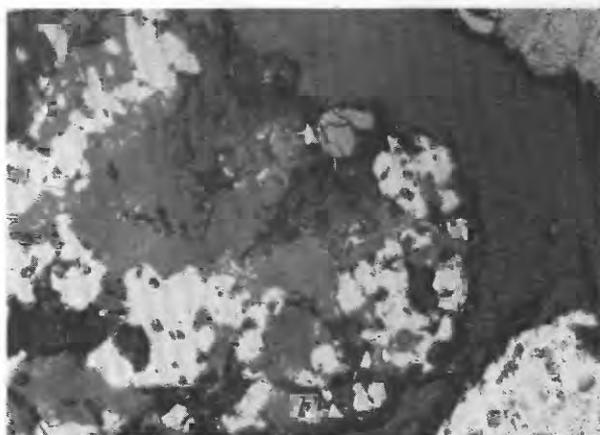
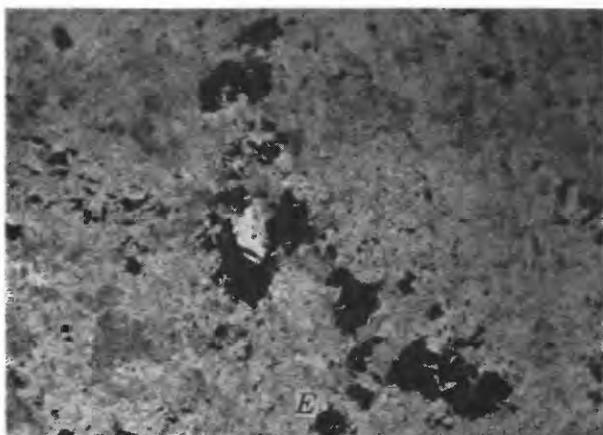
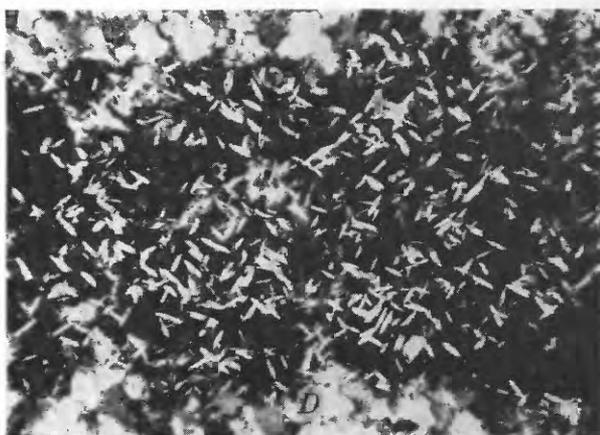
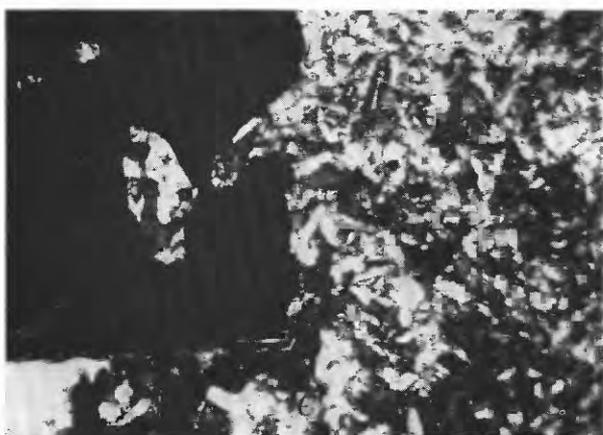
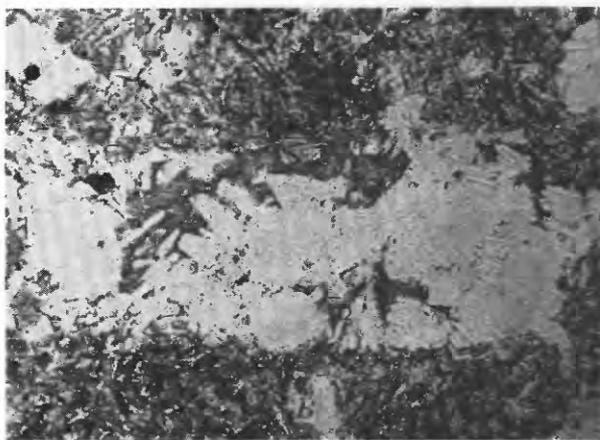
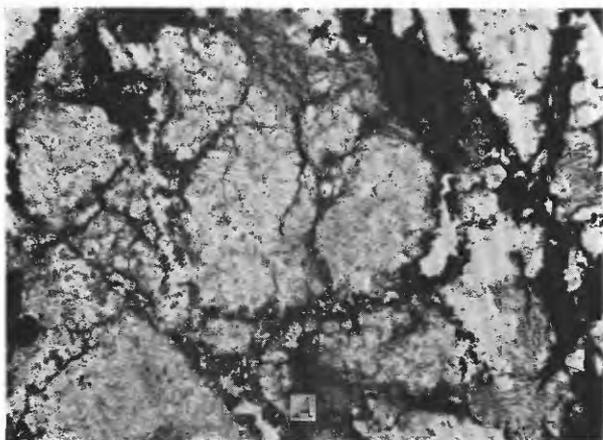
OPAL

In the copper oxide ore, colorless opal [$\text{SiO}_2, n\text{H}_2\text{O}$] and some chalcedony are associated with chrysocolla. Most of the colloidal silica originally in the solutions probably united with copper ions to form chrysocolla and only rarely remained as opal or crystallized as chalcedony or small quartz crystals.

CUPRITE

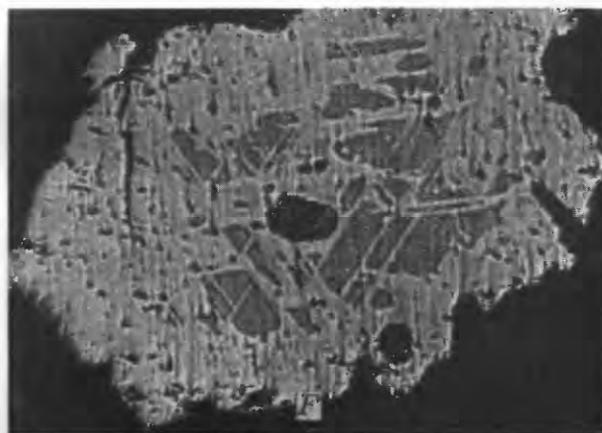
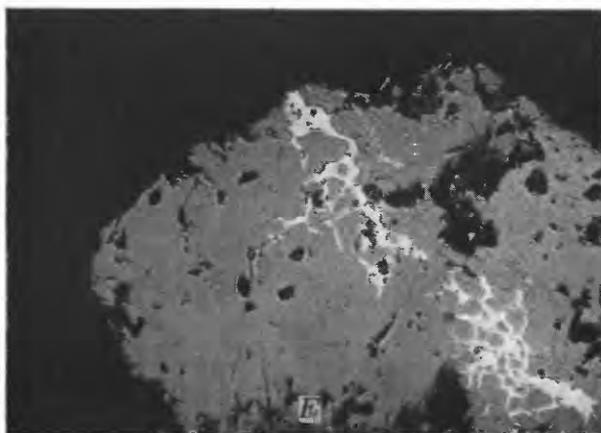
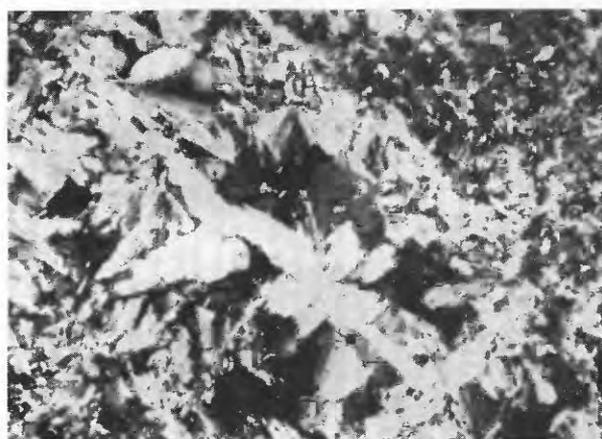
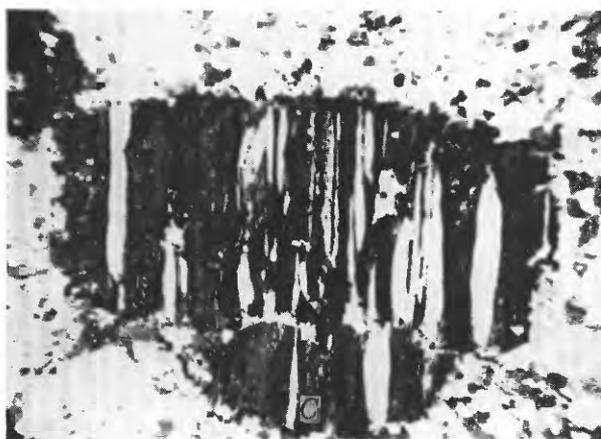
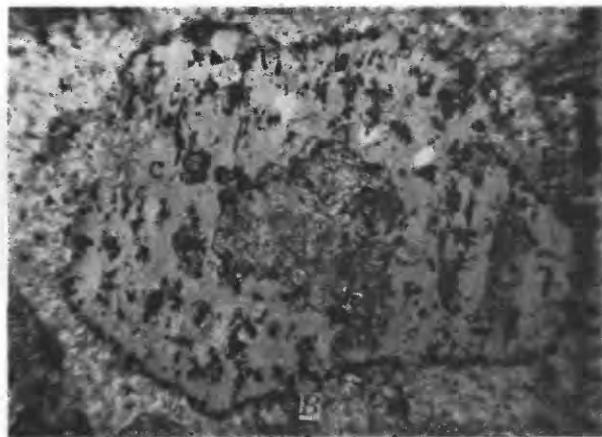
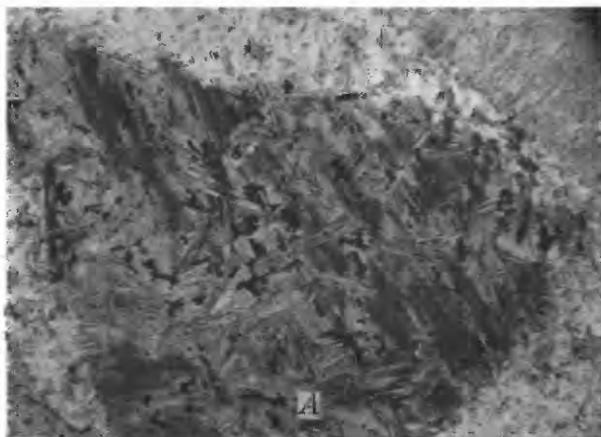
Cuprite [Cu_2O] has been recognized mainly near the bottom of the oxide zone and the top of the supergene sulfide zone where chalcocite frequently shows more or less oxidation to cuprite (pls. 4A, 5D, 5E). In the early stages of oxidation of chalcocite, cuprite forms a complex pattern of dendritic veinlets throughout the chalcocite (pl. 4A). In more advanced stages irregular remnants of chalcocite remain irregularly distributed in the cuprite. Native copper also shows replacement by cuprite.

In the oxide zone a small copper content is often persistent even where no copper minerals may be recognized by ordinary means. Iron oxide is abundant in this material, and it is inferred that earthy cuprite occurs with the iron oxides, thus accounting for the copper.

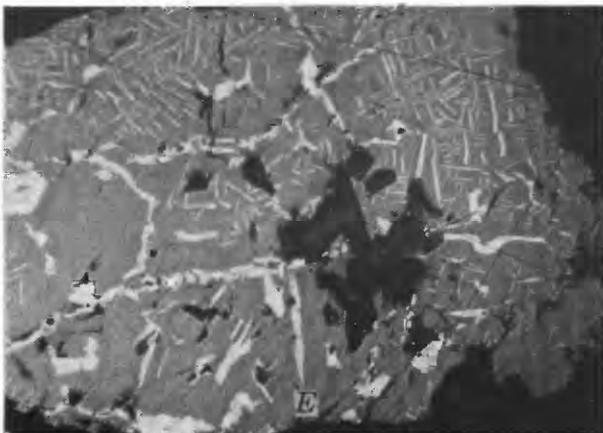
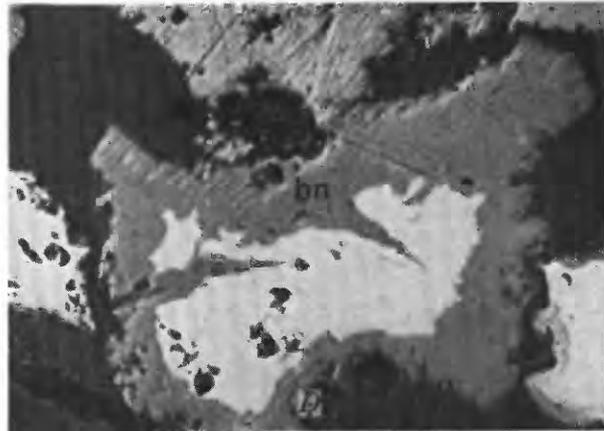
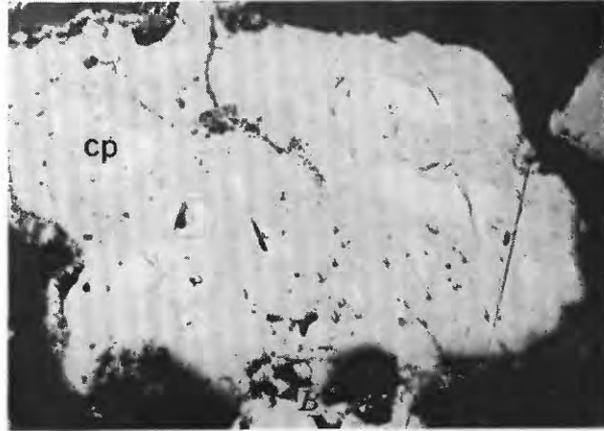
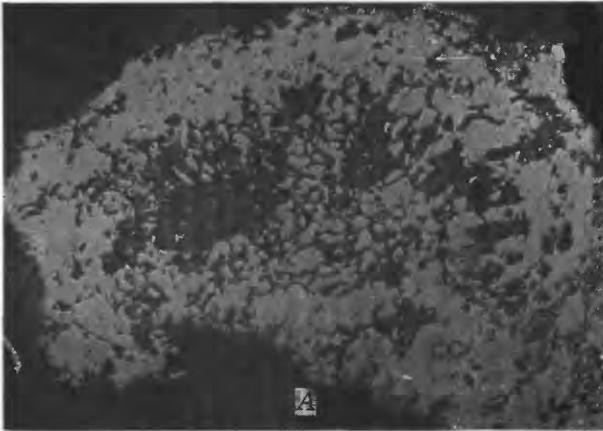


- A. Cracked alunitized and kaolinized porphyry. Cracks marked by iron oxide. From an outcrop in central area of intense alteration. Plane polarized light. $\times 50$.
- B. Alunite pseudomorph after plagioclase. Note lathlike shape of some alunite crystals. Altered monzonite porphyry from outcrop on north side of Red Hill. Crossed nicols. $\times 80$.
- C. Pyrite crystal with an inclusion of alunite. Groundmass is mainly alunite. Outcrop on north side of San Manuel area. $\times 125$.

- D. Altered monzonite porphyry. Outcrop on north slope of Red Hill. Alunite needles (white) in matrix of kaolinite, both occupying the space of a former plagioclase phenocryst. Crossed nicols. $\times 80$.
- E. Sericitized porphyry of the ore zone. Hole 6 at 1,105 feet. Chalcopyrite (black) disseminated in highly altered rock. Typical of the minute grains of sulfide widely distributed in the ore-bearing rock. Plane polarized light. $\times 50$.
- F. Rutile grains in silicate. Hole 5 at 825 feet. The rutile grains (white) often occur in clusters in the silicate, particularly altered biotite. Reflected light. $\times 200$.

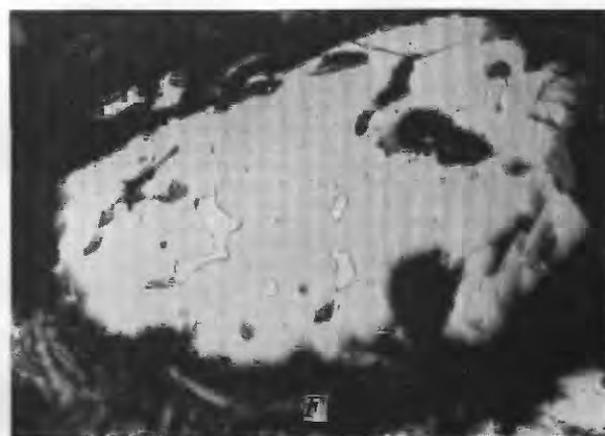
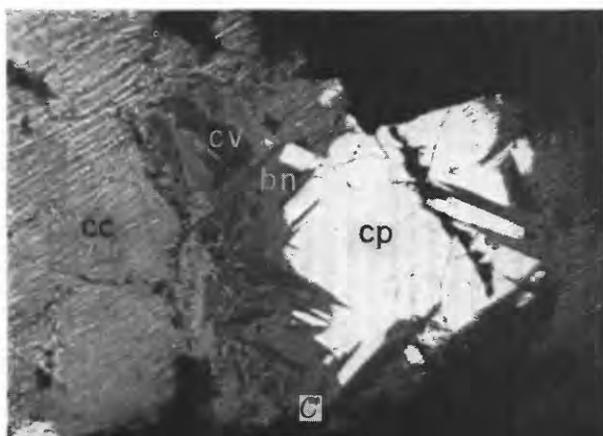
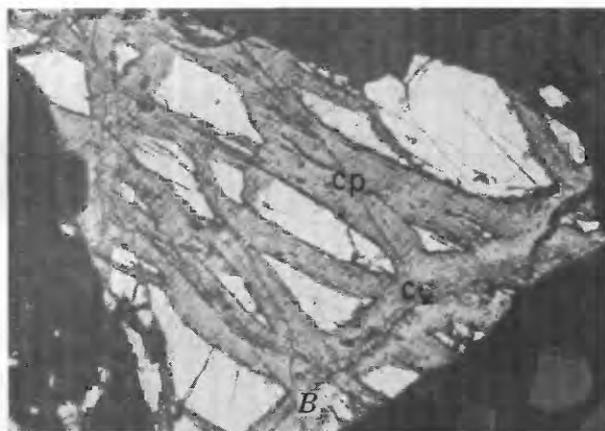
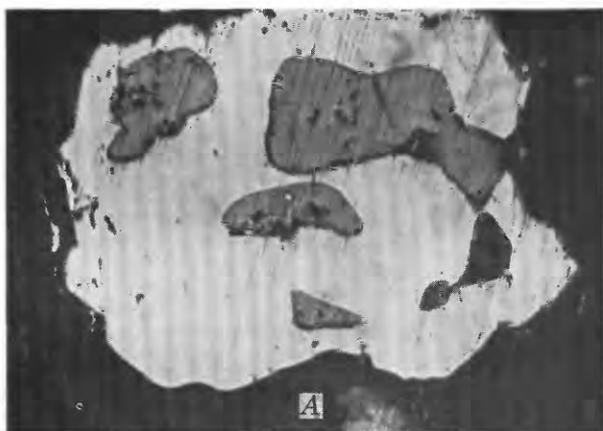


- A. Marginal type of alteration of monzonite porphyry. Hole B at 500 feet. Biotite phenocryst recrystallized to an aggregate of small grains of mica. Plane polarized light. $\times 47$.
- B. Biotite phenocryst altered to epidote (*e*) and chlorite (*c*). Outcrop on north side of San Manuel area. Plane polarized light. $\times 50$.
- C. Altered biotite crystal from marginal type of alteration of monzonite porphyry. Hole H at 970 feet. Lenses of calcite (white) in partly altered biotite. Darkest bands are alternating biotite and chlorite. Crossed nicols. $\times 20$.
- D. Monzonite porphyry of hydromica-pyrite type of alteration. Hole 9 at 650 feet. Coarse hydromica replaced a plagioclase phenocryst that extends from the upper left to low right of photograph. Crossed nicols. $\times 90$.
- E. Secondary sulfide ore. Hole X at 915 feet. Native copper veinlets (white) cut and replace fragments of chalcocite. Reflected light. $\times 325$.
- F. Magnetite remnants in hematite grain. Hole T at 605 feet. Reflected light. $\times 340$.



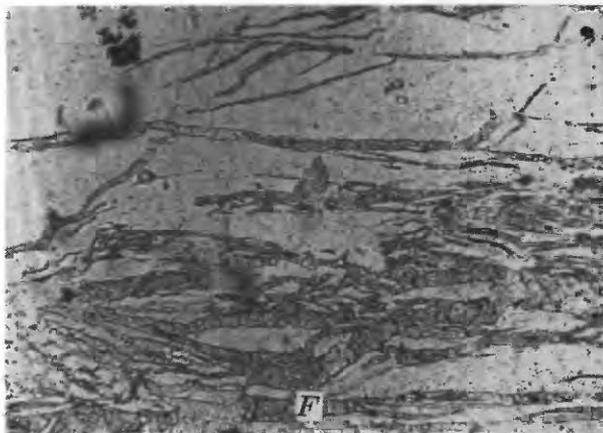
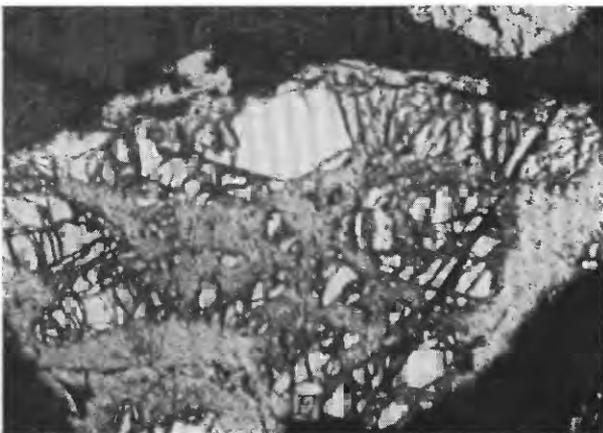
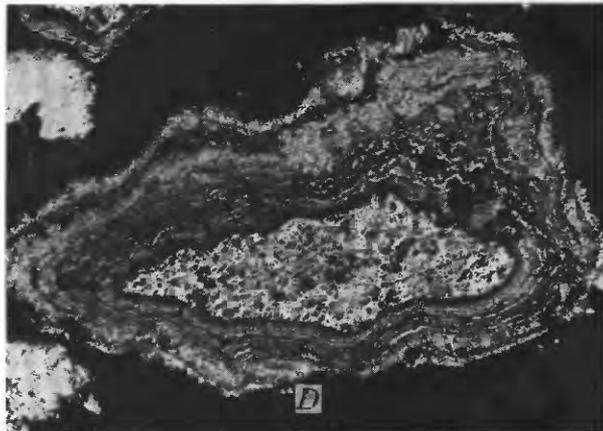
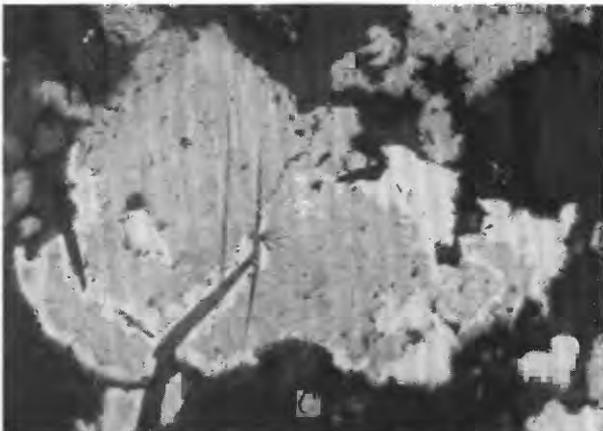
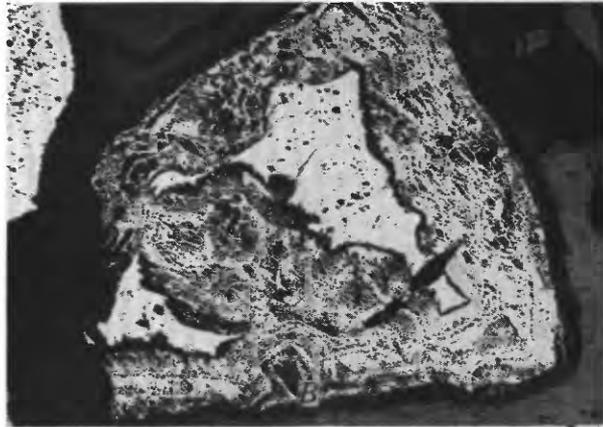
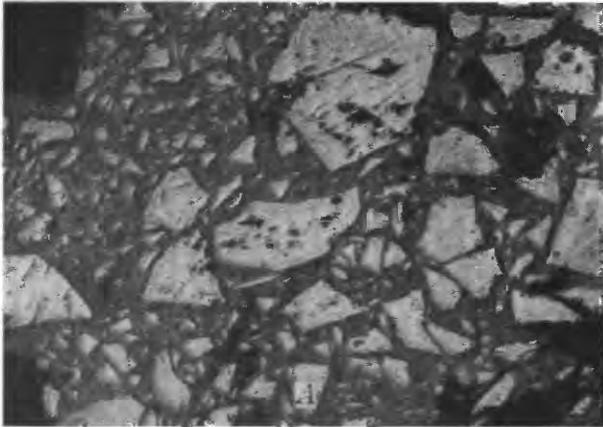
- A. Partly oxidized secondary sulfide ore. Hole M at 553 feet. Network of cuprite (dark) veinlets replacing chalcocite (*cc*). Reflected light. $\times 240$.
- B. Secondary sulfide ore. Hole 6 at 710 feet. Chalcopyrite (*cp*) remnants in chalcocite. Reflected light. $\times 200$.
- C. Secondary sulfide ore. Hole 0 at 1,120 feet. Covellite has partly replaced chalcopyrite. Reflected light. $\times 300$.
- D. Secondary sulfide ore. Hole 6 at 710 feet. Chalcopyrite remnant in bornite (*bn*). Reflected light. $\times 400$.

- E. Exsolution texture. Hole 10 at 1,225 feet. Chalcopyrite as lattice and as stringers along grain boundaries in bornite. Probably a result of overheating in drying concentrate. Reflected light. $\times 500$.
- F. Secondary sulfide ore with remnant. Hole 10 at 995 feet. Part of a chalcocite fragment that has a remnant which is an intergrowth of chalcopyrite (white) and bornite (dark gray). The bornite probably has replaced the chalcopyrite in the primary ore. Chalcocite is supergene. Reflected light. $\times 350$.



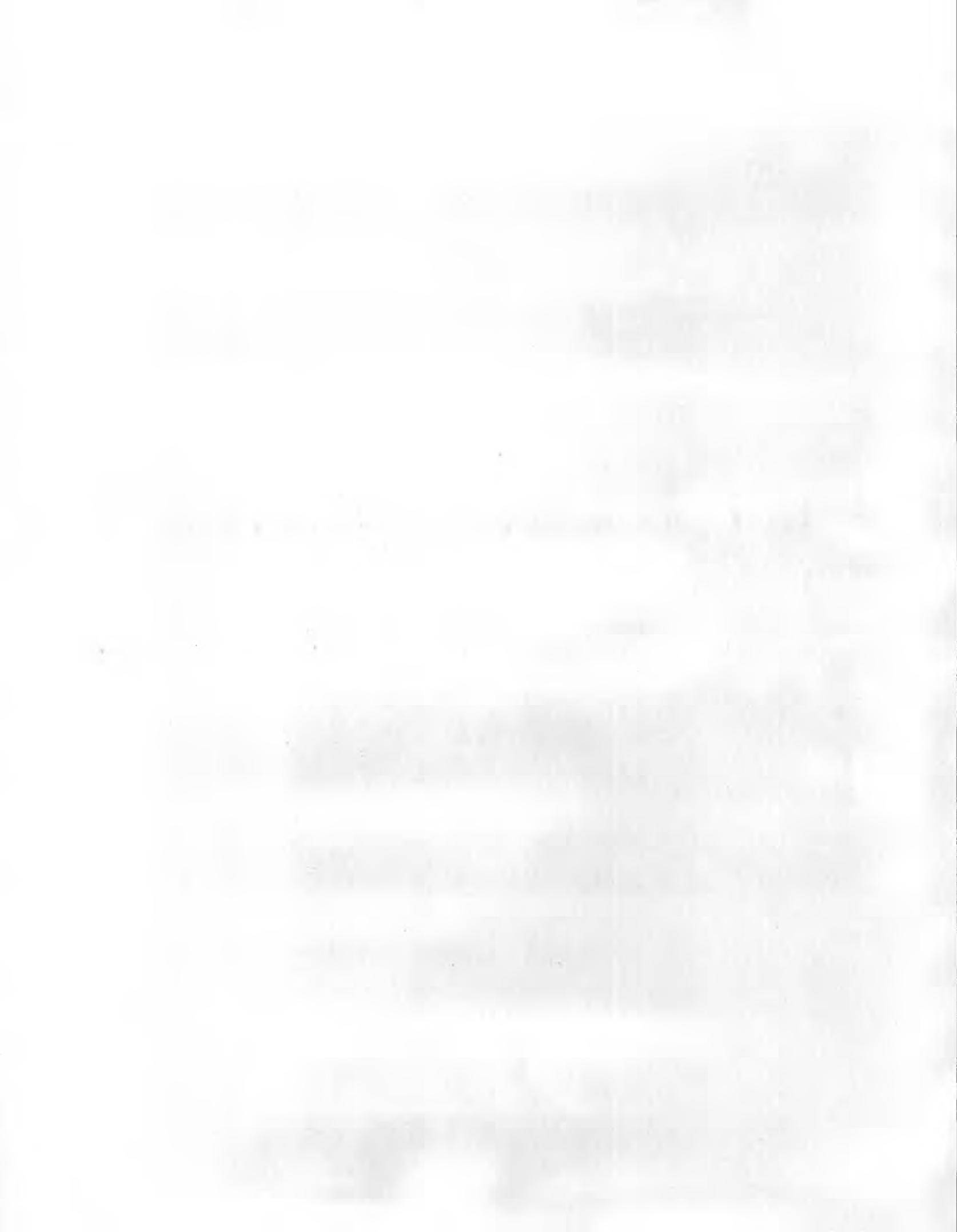
- A. Chalcopyrite inclusions in a pyrite grain. Hole 13 at 1,050 feet. Probably much of the copper in highly pyritic ore occurs in this manner. Reflected light. $\times 100$.
- B. Secondary sulfide ore. Hole 14 at 940 feet. Pyrite partly replaced by veinlets of chalcopyrite (*cp*). Center of veinlet at lower right is occupied by chalcocite (*cc*) not easily distinguished in the photomicrograph. Reflected light. $\times 120$.
- C. Secondary sulfide ore. Hole 6 at 710 feet. Chalcopyrite replaced by bornite (*bn*) which is in turn replaced by dark

- blades of covellite (*cv*), both apparently in turn are being replaced by chalcocite (*cc*). Reflected light. $\times 350$.
- D. Partly oxidized secondary sulfide ore. Hole 10 at 1,015 feet. Chalcocite (white) partly replaced by cuprite (dark gray). Reflected light. $\times 275$.
- E. Partly oxidized secondary sulfide ore. Hole 56 at 510 feet. Chalcocite (*cc*) altered in concentric zones to cuprite (*cu*). Reflected light. $\times 120$.
- F. Primary ore. Hole X at 1,600 feet. Chalcopyrite inclusions in a grain of rutile. Reflected light. $\times 275$.



- A. Oxidation of pyrite. Hole R at 445 feet. Pyrite remnants in goethite. Reflected light. $\times 140$.
- B. Oxidized pyrite. Hole 9 at 635 feet. Iron oxide, mainly goethite, with concentric texture around pyrite remnant. Reflected light. $\times 120$.
- C. Secondary sulfide ore. Hole 13 at 1,050 feet. Native copper (white) that has replaced chalcocite around the outside and along bladelikey gangue, probably sericite. Reflected light. $\times 100$.

- D. Secondary sulfide ore. Hole 2 at 715 feet. Pyrite replaced by chalcocite that developed a concentric texture probably involving minute inclusions of impurities. Reflected light. $\times 200$.
- E. Secondary sulfide ore. Hole 14 at 940 feet. Pyrite remnants in chalcocite. Reflected light. $\times 150$.
- F. Quartz monzonite from the ore zone. Hole 15 at 1,805 feet. Quartz grain shattered and cut by minute series of calcite veins. Plane polarized light. $\times 45$.



MELACONITE

Small amounts of black copper oxide occur with chrysocolla and other copper minerals of the oxide zone, but observations on the surface and in drill cuttings indicate that melaconite [CuO] and impure types such as "copper pitch" are of little importance at San Manuel.

The prevalence of red in some of the surface rocks, particularly on Red Hill, is a conspicuous feature of the San Manuel area. Evidence indicates that this red iron oxide is a mixture of hematite and goethite. A massive vein of iron oxide exposed on the south slope of Red Hill is interpreted as an oxidized pyrite vein. An X-ray determination shows that this particular vein is pure hematite.

Some hematite (variety martite) that was found in drill-cutting concentrates was derived from magnetite by oxidation proceeding along the octahedral planes (pl. 3*F*). Good pseudomorphs of hematite after magnetite were observed in concentrates from hole T. Crystalline hematite (variety specularite) was observed rarely in the San Manuel drill cuttings or on the surface. Peterson (1938a, p. 37) however, reports that it is abundant on the lower levels in the St. Anthony mine where it occurs in massive sulfide shoots as glistening black masses.

ILMENITE

Small amounts of ilmenite [FeTiO₃] occur with magnetite in the intruded diabase that has not been too severely altered. In the more altered specimens the ilmenite has broken down, and its titanium now occurs in leucoxene and less commonly in sphene. Ilmenite also occurs with magnetite in the andesite and basalt lava flows of the region.

MAGNETITE

Magnetite [Fe₃O₄] is a sparse mineral at San Manuel. It was observed in some of the drill cuttings from diabase, often partly altered to hematite (martite).

Magnetite was probably fairly common as an accessory mineral in the igneous rocks of the district, but it has been, for the most part, destroyed by hydrothermal alteration. Where magnetite remains, leucoxene often occurs with it, indicating that the primary titaniferous magnetite has partly broken down and liberated the titanium oxide.

In one thin section of a fragment from 1,175 feet in hole S, magnetite and specular hematite are closely associated with pyrite, chalcopyrite, and quartz, and all are believed to have been introduced during the process of mineralization.

RUTILE

Rutile [TiO₂] is a common accessory mineral in the highly altered igneous rocks of the San Manuel deposit.

The usual occurrence is as clusters of rounded crystals or grains that are largely associated with biotite or former biotite areas (pl. 2*F*). In some of the panned concentrates where other heavy minerals were sparse, a small concentrate was obtained consisting largely of minute rutile grains and in composite samples analyzed for titanium by the Bureau of Mines there is an average of about 0.75 percent titanium oxide. The highest titanium in complete analyses of 8 samples is 0.96 percent, and the lowest is 0.48 percent (tables 2 and 3). Most of this occurs as rutile.

In addition to the stubby rutile crystals, a few examples of long needles of rutile oriented along crystallographic directions of biotite were observed. Rutile liberated in the earliest stages of alteration persists in the most highly altered rocks and at places is closely associated with copper sulfide minerals (pl. 5*F*).

GOETHITE

The prevailing red of many surface rocks and drill cuttings is from goethite [Fe₂O₃·H₂O] colored red by finely disseminated hematite; this observation has been confirmed by X-ray determinations. Examination of polished mounted concentrates under polarized light reveals that the iron oxide grains have the concentric structure characteristic of goethite, and the anisotropism is fairly high. When examined with a comparison eyepiece with a standard goethite on one side, the grays are identical. This contrasts to a marked degree with the white of hematite. Polished specimens of massive red iron oxide show a brecciated structure with a matrix and veins of soft hematite, later than the hard, anisotropic goethite. Veinlets of this red oxide are common in thin sections of rocks from the oxide zone, and minute veinlets with the red oxide give the kaolinite-alunite rock of the most intense stage of alteration a crackled appearance (pl. 2*A*).

Much of the goethite, both red and brown, was formed by oxidation of pyrite (pl. 6*A*). In general, oxidation has been so thorough that no pyrite remains, but some polished surfaces of mounted concentrates reveal remnants of pyrite, and the goethite has a concentric structure related to the pyrite (pl. 6*B*).

PSILOMELANE

Small amounts of psilomelane [BaMn''Mn₈'''O₁₆(OH)₄] were found in the San Manuel drilling, especially in hole M at 510 feet and hole 51 from 500 to 510 feet. The mineral, probably with other associated manganese oxides, is abundant in a series of small veins that are widespread on the west side of Tucson Wash. Some of these deposits were worked on a small scale during World War I, and small piles of ore prepared for possible shipment still remain. Calcite is a characteristic

gangue with the psilomelane, and one of the veins examined also contained barite. A manganese vein was observed along the contact of a rhyolite dike with the pre-Cambrian quartz monzonite, thus showing that the manganese was introduced later than the ore of the San Manuel deposit.

CALCITE

Calcite [CaCO_3] is not abundant in the San Manuel area but occurs in the marginal biotite zone and to a lesser extent in the ore. Vein calcite occurs with manganese oxides, mainly west of Tucson Wash, and it is abundant in the late fault fissures of the St. Anthony where it is often black because of manganese oxides along the cleavage planes.

In thin sections of the surface rocks and drill cuttings, calcite was recognized in veinlets (pl. 6*F*) and as an alteration product of oligoclase and less commonly of other minerals. The calcite veinlets commonly cut all other minerals. Pseudomorphs of feldspar phenocrysts consisting of calcite accompanied by sericite, epidote, and clinozoisite were observed. Calcite also occurs in altered biotite phenocrysts where it forms layers alternating with bleached biotite and chlorite (pl. 3*C*).

Caliche, a characteristic of desert regions, occurs in the soil of much of the area. Calcite also forms the cement in a tuffaceous sandstone that crops out in Tucson Wash north of Tiger.

MALACHITE

Malachite [$\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$] is common in the oxide zone of the ore deposit but rarely is abundant. It has been observed in the drill cuttings as a partial alteration of cuprite, but otherwise its origin is not evident. Some malachite has been deposited by meteoric copper-bearing solutions, for it is found in the conglomerate which was deposited after the ore was formed. In general, silica seems to have been much more readily available during weathering than was the carbonate radical.

AZURITE

Azurite [$2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$] occurs in very small amounts with malachite in drill cuttings. Some fairly good coatings on fractures were observed along the diabase dike on the north side of the ore body; otherwise the mineral is not common in outcrops.

ORTHOCLASE

Orthoclase [$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$] occurs principally in the groundmass of the monzonite porphyry where it forms a very finely granular aggregate with quartz. It is resistant to alteration, and only in the more intensely altered rocks has orthoclase changed to clay minerals,

sericite, and alunite. Orthoclase also occurs in the fresher facies of the quartz monzonite, usually as large, simple, untwinned grains.

Adularia was observed in a few quartz veinlets, but more often the vein orthoclase seems to be the normal variety. Peterson (1938a, p. 40) also observed adularia in veins in deposits of the St. Anthony mine.

MICROCLINE

Microcline [$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$] occurs as coarse grains in the quartz monzonite, with the usual gridiron twinning in all grains. Its alteration is similar to that of orthoclase.

PLAGIOCLASE

Plagioclase [(Na,Ca)Al(Si,Al)Si₂O₈] (variety calcic oligoclase, Ab₇An₃) is an essential mineral in the quartz monzonite (Oracle granite) and in the monzonite porphyry.

In the monzonite porphyry it forms characteristic phenocrysts and occurs to some extent in the groundmass. It is readily attacked by hydrothermal solutions and may be represented by pseudomorphs of sericite, hydromica, kaolinite, chlorite, alunite, and lesser amounts of other secondary minerals (pls. 2*B*, *D*, and 3*D*). The less altered crystals are clouded with allophane inclusions and disseminated sericite shreds, the latter commonly oriented along crystallographic directions. In the northern part of the San Manuel property the phenocrysts are altered to epidote, clinozoisite, and calcite.

More calcic plagioclase undoubtedly occurs in the diabase dikes and basic lava flows of the region.

PYROXENE

Pyroxene [complex silicate of Ca, Mg, Fe, and Al] is lacking in the rocks of the San Manuel area except in diabase and in basic lava flows. In these rocks it has been largely destroyed by alteration to chlorite and other ferromagnesian alteration products.

ZIRCON

Zircon [Zr SiO_4] is a characteristic accessory mineral in the quartz monzonite and the monzonite porphyry. Detailed studies of several panned concentrates by Raymond Rantala in the laboratories at the University of Minnesota showed that zircon was present in all samples and was exceeded in amount only by rutile. Zircon crystals from the quartz monzonite are brown and bluish red and are simple in crystal form. The prisms are usually terminated by bipyramids of the same order, but a few are terminated by bipyramids of a different order. The zircon crystals from the monzonite porphyry are colorless and have many bipyramids at their terminations, giving many small faces.

Spectroscopic determinations of the amount of zirconium in eight samples used for rock analyses show as much as 0.02 percent.

CLINOZOISITE

Clinozoisite [$\text{Ca}_2(\text{AlOH})\text{Al}_2(\text{SiO}_4)_3$] occurs as coarse grains with epidote in the marginal biotite stage of alteration, mainly on the hill that lies between Red Hill and Tiger. The two minerals occur together in some thin sections as clusters of grains that have replaced oligoclase and biotite (pl. 3B).

EPIDOTE

The occurrence of epidote [$\text{Ca}(\text{Al,Fe})\text{OH}\text{Al}_2(\text{SiO}_4)_3$] with clinozoisite is noted above. Epidote is not common in the rocks of the ore zone, but small quantities were observed in some thin sections that show a complex of alteration products with less severe sericitization than occurred in most of the ore. Calcite in small amounts is almost always present with either epidote or clinozoisite in such rocks.

Epidote occurs as much larger grains than other alteration products. At places single grains occupy the area of a former small feldspar phenocryst. In former biotite areas the grains are often embedded in chlorite.

MUSCOVITE AND SERICITE

Muscovite [$\text{H}_2\text{KAl}_3(\text{SiO}_4)_3$] occurs in small amounts as a primary mineral of quartz monzonite, but it is more abundant as secondary sericite, which occurs in all the hydrothermally altered rocks.

Sericite is exceedingly abundant and is characteristic of the copper ore zone where it largely replaced the feldspars of the original rocks. It also was formed from biotite by progressive bleaching; so that excellent pseudomorphs of colorless mica after biotite phenocrysts were frequently observed in thin section. Some pseudomorphs consist of alternating layers of sericite and chlorite.

The usual fine-grained, flaky, or shredlike sericite occurs especially as a replacement of oligoclase phenocrysts of the monzonite porphyry, forming good pseudomorphs. Equally common are pseudomorphs of clay minerals after plagioclase that are in turn partly replaced by coarser flakes of sericite. Sericite forms veinlets in fractured quartz grains but does not replace quartz appreciably. In the examples of most intense sericitization within the ore zone, the resulting rock may consist principally of sericite and primary and secondary quartz.

At places sericite is more abundant along small quartz veins than elsewhere in the rock. This suggests that the introduction of quartz and the formation of sericite were closely related, although sericite is much more abundant

and widespread than introduced quartz. Pyrite and chalcopyrite are closely related to abundant sericite in time of formation, and sericite is often much coarser where associated with abundant sulfide. Sulfide is not related to the disseminated sericite that occurs in other types of alteration. Sericite occurs in clay minerals as veinlets and as coarse flakes; in the more intensely altered rocks many minute vugs are lined with sericite crystals.

BIOTITE

Biotite [$\text{H}_2\text{K}(\text{Mg,Fe})_3\text{Al}(\text{SiO}_4)_3$] is the principal ferromagnesian mineral of the quartz monzonite and monzonite porphyry. It occurs as large flakes of irregular outline in the coarse-grained quartz monzonite. In the monzonite porphyry it forms characteristic crystals of hexagonal outline with a maximum diameter rarely exceeding 0.4 millimeter and, in addition, small flakes are abundant in the groundmass. The biotite imparts a dark color to the hanging-wall rock of the ore deposit and to moderately altered rock away from the ore deposit. In some specimens the abundance of biotite in the groundmass suggests the possibility that part of it is introduced, probably as a deuteric product.

Light brown aggregates of biotite represent the recrystallization of biotite phenocrysts (pl. 3A).

CHLORITE

Chlorite [complex silicates of Al, Mg, Fe, and H] is the characteristic ferromagnesian mineral of the hydrothermally altered rocks of the less intense stages. In the more intensely altered rocks the ferromagnesian minerals have been largely destroyed. Several varieties of chlorite were recognized, especially delessite, penninite, and less commonly antigorite. In the less intense stage, particularly as exposed on the hill between the San Manuel deposit and Tiger, biotite phenocrysts of the porphyry are altered to chlorite, epidote, and clinozoisite (pl. 3B).

In altered diabase the ferromagnesian minerals have largely altered to chlorite and, locally, pseudoamygdules of chlorite have formed by replacement in the diabase.

Many thin sections show chlorite as a replacement or alteration in plagioclase where it occurs as disseminated flakes, stringers, and veinlets cutting partly altered phenocrysts. In a few thin sections chlorite was observed as a vein mineral with quartz and less commonly with sulfides and sericite. Locally in the veins chlorite forms coarse radial aggregates. It seems probable that veinlets of penninite represent deposition of magnesia carried out from zones of intense alteration.

KAOLINITE

The intensely hydrothermally altered igneous rocks of the San Manuel area contain much kaolinite.

[$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$]. Most of the kaolinite is of hydrothermal origin, as it is present in the drill cuttings below the zone of weathering. Decomposition of pyrite to form sulfuric acid that may in turn attack silicates and form kaolinite is a distinct possibility, particularly in the kaolinite-alunite type of alteration. No criteria were discovered to distinguish such kaolinite from that formed by hydrothermal solutions.

Pseudomorphs of kaolinite after plagioclase are common, consisting of a mat of exceedingly minute flakes of kaolinite which may be recognized only at high magnification. Less commonly, the kaolinite consists of small, wormy or accordionlike aggregates. Similar alteration of orthoclase to kaolinite is found only in advanced stages. Some kaolinite is in veinlets.

DICKITE

Dickite [$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$] was identified in a few thin sections, usually with alunite, in the most intensely altered rocks. Sericite, associated with dickite and alunite, is clearly later than either of them; thus indicating the hydrothermal origin of dickite.

HALLOYSITE

In a few thin sections small amounts of isotropic clay mineral with index close to balsam were recognized as halloysite [$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$], but material suitable for an X-ray determination was not found. Small halloysite veinlets cut all other minerals in the alunite-kaolinite rock and are probably of supergene origin.

ALLOPHANE

Allophane [$\text{Al}_2\text{O}_3 \cdot x\text{SiO}_2 \cdot n\text{H}_2\text{O}$] was recognized in feldspar that has a dusty appearance in thin section. On examination at high magnification, particularly with an oil immersion lens, this effect was found to be a result of innumerable tiny isotropic flakes of allophane that has an index well below that of orthoclase. Some veinlets are composed largely of allophane with lesser amounts of other clay minerals. Minute inclusions of allophane are common in the quartz of the highly altered rocks.

ENDELLITE

Endellite [$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 4\text{H}_2\text{O}$] occurs as an alteration product of plagioclase in a thin section from a depth of 665 feet in hole H. Potash clay lies in a matrix of the endellite, and coarse hydromica veinlets cut both endellite and potash clay.

MONTMORILLONITE (BEIDELLITE, NONTRONITE)

This group [hydrous silicate of Al, Fe, Ca, Mg, and Na] is variable in composition and it is difficult to give a general formula.

A little very fine-grained beidellite was seen in a few thin sections. It was formed from sericite by alteration around the edges of the flakes.

In an example of intense sericitization of quartz monzonite from the ore zone, a little montmorillonite was observed as minute but fairly abundant pinkish blades in a felted mass of sericite.

In some specimens biotite has altered to a very fine-grained brown mineral like kaolinite. This was identified as nontronite, although samples suitable for an X-ray determination were not obtained. Nontronite usually occurs where oxidation has been extensive, in general near iron oxide derived from pyrite. Not all nontronite, however, appears to result from weathering, for in a thin section of a fragment of monzonite porphyry from a depth of 630 feet in hole 14 biotite has altered to light-orange pseudomorphs, with yellow to amber interference colors. These are believed to be nontronite of hydrothermal origin because evidence of weathering of the rock is lacking.

HYDROMICA (ILLITE)

This group [hydrous silicate of Al, Mg, K] is variable in composition and it is difficult to give a general formula.

Many thin sections of altered rocks contain a very fine-grained flaky mineral which has the index and general appearance of kaolinite but has a birefringence slightly above that of kaolinite. This results in first-order yellows under crossed nicols at high magnifications. Lovering (1949, fig. 12, and personal communication) has called this material potash clay. Generally, it occurs as a mat of extremely fine flakes but may also show a vermicular or accordionlike structure similar to that shown by kaolinite. There is no doubt that the mineral is very closely related to kaolinite in the rocks of the San Manuel area for it not only appears much like kaolinite, except for the interference color, but its occurrence is practically identical. It appears to form a continuous gradation with kaolinite, but the extremely fine grain and the confusion of associated alteration products make further definition of the properties almost impossible. In some thin sections it is possible to see progressive alteration from allophane and kaolinite to potash clay, to hydromica, and even to sericite. Minute veinlets or seams of potash clay were also observed cutting a mat of sericite. One thin section showed areas of potash clay with embedded calcite grains, indicating a close relation in origin.

In the highly altered rocks, particularly of the pyritic zone, light-gray pseudomorphs with a slight greenish cast frequently occupy the area of former plagioclase phenocrysts (pl. 3D). Microscopic examination shows that the index of refraction and the birefringence are below those of sericite. This corresponds well with the characteristics of hydromica. In many sections biotite is altered to pseudomorphs of muscovite and, where

alteration has been severe, to material of lower index and birefringence, which is obviously a further alteration of muscovite. It is also possible that hydromica was altered to muscovite where potash-bearing solutions entered the rock.

The least altered specimen of the quartz monzonite which was obtained showed much alteration of plagioclase to hydromica. This mineral occurs in rocks representing all stages of alteration but is especially characteristic of the highly pyritic rocks that occur mainly as the footwall of the ore body. It is often difficult to distinguish between hydromica and very fine grained sericite which gives lower interference colors than normal. Patient comparison of the indices where the two occur together is necessary. Coarse-grained hydromica occurs with quartz and pyrite as a late alteration and cuts and replaces kaolinite and other clay minerals.

The hydrothermal alteration of biotite has proceeded by gradual stages from the primary biotite to a recrystallized lighter-brown biotite (pl. 3A) from which rutile has segregated, to a very light brown mica of lower index and slightly lower birefringence. The more altered grains are green, but the birefringence shows that the mineral is not chlorite. These grains show fairly good pleochroism. Inasmuch as these changes accompany the formation of other hydrous minerals and a progressive elimination of iron, it is believed that the mineral corresponds to hydrobiotite. Unfortunately, the fine grain and confused aggregates of the alteration products do not permit separation of this material for detailed study.

ZUNYITE

In a thin section from a depth of 650 feet in hole 9, a small mass of zunyite $[Al_{13}Si_5O_{20}(F, OH)_{18}Cl]$ was identified by T. S. Lovering. This section is from highly altered monzonite porphyry of the hydromica stage of alteration and the small mass of zunyite occurs in a microvug later than the sericite of the section but is in turn cut by a fluorite veinlet.

CHRYSOCOLLA

The most abundant mineral of the oxide zone at San Manuel is chrysocolla $[CuO \cdot SiO_2 \cdot nH_2O]$, with which more or less indefinite copper silicates are associated. The usual occurrence is as small scales and stains on the fractures throughout the rock. In rare samples it was possible to separate small fragments of comparatively pure chrysocolla. Most of the mineral seems to have been deposited by solutions which moved the copper, at least, a short distance from the parent primary or supergene sulfide minerals; however, it was also noted as a replacement of chalcocite.

A thin section of chrysocolla veinlets in porphyry from a dump north of hole 8 showed that two varieties occur in the same rock. The older occurs along the sides of the veinlets and is highly birefringent. The remainder of the veinlet under crossed nicols resembles chert and has a low birefringence. These are similar to two of the several varieties of chrysocolla noted by Schaller (1931, p. 112).

BARITE

Barite $[BaSO_4]$ occurs in a vein with calcite and psilomelane on the west side of Tucson Wash. Peterson (1938a, p. 42) also notes that it occurs as large tabular crystals in the siliceous filling of vein breccia at the Collins mine at Tiger. A pit at the northwest border of the San Manuel area and southwest of Tiger shows coarsely crystalline barite with fluorite in a quartz vein. At San Manuel in a thin section from a depth of 1,135 feet in hole 2, barite occurs in quartz-sulfide veinlets in highly sericitized rock. Minute crystals believed to be barite occur as clusters in alunite from a porphyry dike on the north slope of Red Hill and also in introduced quartz from rock exposed near hole 16. In all examples, barite was introduced at a late stage.

ALUNITE

Abundant alunite $[K_2Al_6(OH)_{12}(SO_4)_4]$ in the hydrothermally altered rocks of the San Manuel area is confined mainly to the zone of intense alteration east of Red Hill and to a lesser extent to the pyritic type of alteration. Part of the alunite is so fine grained that it is difficult to identify in thin section even when X-ray determinations prove its existence. The index is slightly above that of kaolinite with which it is closely associated, and if larger grains can be found the birefringence gives interference colors above the gray and white of kaolinite.

In the highly altered, light-gray rock east of Red Hill, kaolinite, alunite, and quartz are the abundant minerals. If all of the sulfate radical in the analysis of rock from the kaolinite-alunite zone is assigned to alunite, the percentage present is 19.3.

JAROSITE

Jarosite $[K_2Fe_6(OH)_{12}(SO_4)_4]$ occurs in small amounts as a product of oxidation of pyrite. It is more abundant in the kaolinite-alunite rock north of the ore zone. For some reason sulfates seem to have been more stable in this zone of alteration and remain as minerals in the altered rock.

FLUORITE

Fluorite $[CaF_2]$ was observed in a chalcedony vein in the northwestern part of the San Manuel area not far from the southwestern edge of Tiger. Peterson

(1938a, p. 36) notes that it is abundant as microscopic grains in the vein matter of the St. Anthony mine, the bulk having been deposited at a late stage with clear, coarse-grained quartz. In thin sections of the drill cuttings, fluorite is rare but was observed in late veinlets and as grains in the alteration products. In view of the late epithermal mineralization of the St. Anthony deposit, it may be that fluorite, with some late quartz, barite, and zunyite, formed in the San Manuel deposit during a second period of hydrothermal activity

ORE DEPOSITS

HISTORY OF DISCOVERY

Red Hill, which owes its color to oxidation of the pyritic zone of the deposit, is a conspicuous landmark on the San Manuel property (pl. 1). Across a gully at the foot of the south slope of Red Hill is a chrysocolla-stained outcrop, which measures about 380 by 400 feet and forms a roughly triangular area (pl. 1). About 600 or 700 feet east of this triangular area are other smaller copper-stained exposures.

For more than a half century these showings of copper attracted the attention of prospectors who tested them by pits, other shallow workings, and a few exploratory drill holes. These prospecting efforts had failed to find shipping ore, and no attempt had been made to prove that the showings were the outcroppings of a large, low-grade ore body. Thus, at the time of Pearl Harbor, the San Manuel property was only a prospect.

World War II focused attention on the possibility of producing copper from low-grade oxide ore at San Manuel and provided the incentive for the exploration and development work that within a 6-year period transformed San Manuel from a raw prospect into one of the three largest known copper deposits in the United States.

The finding of so large an ore body at this site has created much interest among those in the mining profession. The natural question is; Who made the discovery and how was it done? There is no simple answer, as will be shown by the following review. The discovery was, in fact, a gradual process that took place over a considerable time, with contributions by many individuals and organizations.

Peterson (1938a, p. 25) states that Frank Shultz located claims on the Collins vein of the present St. Anthony mine in 1879 and other claims in 1881 and 1882. As the copper-stained outcrop of the San Manuel deposit is less than a mile south of the St. Anthony mine, it is logical to infer that this copper-stained rock did not escape attention and that probably some of the oldest test pits were made in the early 80's. Work at the St. Anthony mine has been practically continuous since 1879, as noted in some detail

by Peterson. Henry W. Nichols, one of the owners of the San Manuel claims in 1942, stated (personal communication) that a number of old monuments and discovery cuts were found on Red Hill and also on the outcrop of the San Manuel ore body. The copper outcrop apparently had claims located on it several times, but not enough work was done to secure patents, and the locations were allowed to lapse. Finally, some of the claims on San Manuel ground were staked in 1906 and have been held more or less continuously.

It is known that two drill holes were put down in the area in 1917, and one of these holes is marked by a casing still visible near pits in copper-bearing rock along the diabase dike a short distance north of hole 8. Results of this drilling were unsatisfactory because the holes were in the pyritic type of mineralized zone that forms the footwall of this part of the ore body.

The following statement (personal communication) by Mr. Nichols gives the history of the San Manuel claims from which the name of the exploration and the corporation was derived.

The original San Manuel Claims No. 1 to No. 5 (inclusive) were located by Anselmo Laguna, July 1, 1925. James M. Douglas bought a one-third interest on June 18, 1926, and another one-third interest on August 19, 1939. James M. Douglas and Burns Giffin bought the remaining one-third interest on October 25, 1939. Douglas and Giffin deeded Victor Erickson a one-fourth interest in the above claims on March 29, 1940. The three partners admitted Henry W. Nichols to partnership as owner of one-fourth interest in August 1942. Other adjacent claims to bring the total up to 21 were later located.

Nichols was admitted to supply technical skill to the partnership. He sampled the outcrops and submitted a report to the Reconstruction Finance Corporation with a request for a loan to develop the ore body by drilling. This is the first step on record in the work that led to the discovery, and Mr. Nichols is entitled to much credit for energetically pursuing the exploration of the claims. Because many steps were involved in the discovery, a chronological account of information taken from the file of the Geological Survey is given below. The writer is greatly indebted to Ralph S. Cannon, Jr., commodity geologist for copper during most of the exploration, for help in obtaining the following data:

SOME IMPORTANT DATES IN THE EXPLORATION

October 11, 1942: Report on the San Manuel group of claims, Mammoth, Ariz., by Henry W. Nichols in support of an application to the Reconstruction Finance Corporation for a development loan.

January 22, 1943: William B. Maitland examined the Nichols report for the RFC.

February 10, 1943: A letter from Lynn Hersey, assistant chief, Primary Production Branch, Copper Division, War Production Board, to Burns Giffin, one of the owners, asking for additional information on the property.

February 21, 1943: Letter from Henry W. Nichols, in reply to Lynn Hersey, outlining the proposed drilling program.

February 24, 1943: Memorandum from Lynn Hersey to Ralph S. Cannon, Jr., U. S. Geological Survey, expressing interest in the possibility of quick production from the property by shovel operations and leaching vats, and requesting an examination and opinion by the Geological Survey.

March 1, 1943: Letter from Ralph S. Cannon, Jr., to Lynn Hersey saying that the San Manuel property would be examined. Letter of same date by Cannon requesting B. S. Butler and N. P. Peterson, U. S. Geological Survey, to examine and report on the property.

March 6-19, 1943: N. P. Peterson and B. S. Butler briefly studied, mapped, and sampled the outcrops of the San Manuel deposit, in general confirmed Nichols' geologic interpretation, and concluded that the deposit offers " * * * a possibility of low-cost mining operation that merits further investigation." Their Memorandum Report on the San Manuel Property, dated March 19, 1943, was sent to the Bureau of Mines and the War Production Board. This report stated that " * * * the outcrop as a whole can be fairly expected to grade 1.00 percent or better * * *" at the surface, and recommended exploration for additional information on content at depth, and detailed geologic study to furnish a basis for such an exploration program.

April-November 1943: It is known that during this period the Copper Division, War Production Board, sought means to have test drilling done at San Manuel.

May 22-26, 1943: T. L. Chapman and W. D. Hughes, Tucson office, U. S. Bureau of Mines, examined the property, reviewed the Peterson-Butler and Nichols reports, and recommended a preliminary drilling program. Their report was transmitted July 17, 1943.

November 23, 1943: U. S. Bureau of Mines began drilling. Authorization was for five holes of about 300 feet in depth. C. A. Kumke, project engineer, Project no. 1466.

December 21, 1943: D. H. Kupfer assigned by the Geological Survey to study drill cuttings from the Bureau of Mines holes.

January 15, 1944: Hole 5 stopped at 200 feet by exhaustion of project funds. The following summary shows the importance of the results of the drilling:

- Hole 1. Sericitized monzonite porphyry from 38 to 305 feet, averaged 0.84 percent copper.
- Hole 2. Sericitized monzonite porphyry from 0 to 272 feet, averaged 0.89 percent copper. Sericitized quartz monzonite from 272 to 300 feet, averaged 0.75 percent copper.
- Hole 3. Sericitized monzonite porphyry from 51 to 295 feet, averaged 0.95 percent copper. Sericitized quartz monzonite from 295 to 325 feet, averaged 1.43 percent copper.
- Hole 4. Slightly to moderately altered monzonite porphyry from 218 to 350 feet, averaged 0.55 percent copper.
- Hole 5. Altered monzonite porphyry from 123 to 200 feet, averaged 0.24 percent copper.

The rock above the footages cited was Gila (?) conglomerate.

February 9 through March 1944: Plane table geologic map prepared by D. H. Kupfer and G. L. Quick, U. S. Geological Survey.

February 14, 1944: D. H. Kupfer supplied memorandum stating that drill data and geologic map suggest the possibility of considerable chrysocolla ore averaging about 1 percent and extending to a depth of 700 feet, and the possibility of slight chalcocite enrichment at 700 feet, with primary sulfide ore below.

March 28, 1944: Bureau of Mines allotted money for further drilling to cut sulfide zone. Thomas L. Chapman, project engineer.

April 7, 1944: J. H. Hedges and T. C. Denton of the Bureau of Mines and D. H. Kupfer and N. P. Peterson of the Geological Survey worked out plans for the additional drilling. Hole 6 was designed to cut the sulfide zone to give some idea of the general grade of copper sulfide.

May 15, 1944: Report on the geology at San Manuel by D. H. Kupfer submitted to the Geological Survey and the Bureau of Mines. This report discussed the problem, recognized by the geologists and engineers at an early date, of whether the occurrence of copper mainly as films of chrysocolla on fractures meant that the copper was introduced into the outcrops by copper-bearing ground waters rather than left in place as a residue from the weathering of a copper-sulfide ore body in place. The report favored the interpretation that the chrysocolla ore would give way downward to sulfide ore of about the same grade.

May 27, 1944: Sulfide ore was penetrated for the first time. This in hole 6 at 685-690 feet. The zones penetrated by the hole are as follows:

| | Depth (feet) |
|--|--------------|
| Gila(?) conglomerate----- | 0-160 |
| Zone of oxidation. Assays 205-680 ft. give an average copper content of 0.797 percent----- | 160-180 |
| Secondary sulfide zone, some oxidation. Average copper content 1.02 percent----- | 680-1,020 |
| Zone of variable weak enrichment, plus some oxidation. Mainly pyrite ore originally. Average copper content 0.728 percent----- | 1,020-1,170 |
| Zone of partly oxidized pyritic ore. Average copper content 0.202 percent----- | 1,170-1,405 |

June 1944: Property brought to the attention of the Magma Copper Company, presumably by Henry W. Nichols, a partner, as previously noted. Mr. Nichols was also an employee of the Magma Copper Company. Investigation for Magma made largely by J. K. Gustafson.

July 8, 1944: Supplement to Kupfer's report of May 15, 1944, described studies of polished surfaces of mounted concentrates by M. N. Short that proved the presence of supergene chalcocite. G. M. Schwartz was assigned by U. S. Geological Survey to San Manuel to replace D. H. Kupfer, called to active duty in the Navy.

August 1944: Bureau of Mines received additional allotment of funds to carry on the drilling.

August 31, 1944: Magma Copper Company agreed to purchase of the property from the owners.

December 1944: Drilling begun by Magma Copper Company. Drilling on adjacent ground was begun a short time later by the Anaconda Copper Mining Company under the name of Houghton Group.

February 2, 1945: Bureau of Mines drilling ended by exhaustion of allotted funds. Further work unnecessary because of Magma exploration. For report, see Chapman, T. L., San Manuel copper deposit, Arizona, U. S. Bureau of Mines, Rep. of Inv. 4108, August, 1947.

April 1945: Publication of Geology of the San Manuel area, Pinal County, Arizona: U. S. Geol. Survey, Strategic Mineral Investigations, Preliminary maps 3-180, by G. M. Schwartz.

September 1945: San Manuel Copper Corporation organized as a subsidiary of Magma Copper Corporation, to carry on the exploration.

February 17, 1948: Drilling program completed by San Manuel Copper Corporation. Shaft 1 was started later in 1948.

The foregoing chronology does not necessarily include all of the significant steps in the exploration.

Bureau of Mines, War Production Board, and company files, as well as the memory of individuals, might supply other important information.

The low-grade chrysocolla-bearing rock was trenched and test-pitted before 1900, but this material was far from commercial grade at the time. Indeed, the value of the chrysocolla rock continues in doubt because of metallurgical difficulties in handling low-grade oxidized copper ore in which the principal mineral is chrysocolla. A reappraisal of this material was stimulated by the copper shortage brought on by World War II.

The five shallow drill holes put down by the Bureau of Mines showed continuous low contents of oxide copper in all footage below the conglomerate; so, the possibility of an enriched sulfide zone beneath was evident. When the first deeper hole struck chalcocite ore, the possibility became a reality, and perhaps it may be said that this was the most important milestone in the discovery because once the existence of the secondary sulfide zone was proven, it became evident that the deposit had real possibilities. Bureau of Mines records furnished by J. H. Hedges, at that time district engineer, show that hole 6 at 685 feet was the first to cut sulfide ore. The date was May 27, 1944.

In reviewing the history of the discovery, it seems to the writer that so many organizations and individuals played a part, that it is impossible to record and acknowledge the role of each. Certainly, credit is due to the partners (James M. Douglas, Victor Erickson, Burns Griffin, and Henry W. Nichols) whose faith in their claims aroused the War Production Board's interest in the property, and thus led directly to the Geological Survey investigation and the Bureau of Mines decision to drill. The results of the first drilling were so encouraging that subsequent events followed almost as a matter of course, except perhaps the courageous decision of the Magma Copper Company to spend the large sums necessary to develop the deposit to its present importance.

LOCATION AND GEOLOGIC SETTING

The San Manuel ore body is mostly in sec. 35, T. 8 S., R. 16 E., Pinal County, Ariz. (pl. 1). There is a small lean extension in sec. 34 and possibly a little of the body in sec. 36. The deposit, as now known, extends about 6,800 feet in a direction N. 60° E.

All but a very small part of the ore body is hidden beneath a cover of conglomerate that reaches a thickness of more than 1,000 feet. Beneath the conglomerate, parts of two igneous rock masses make up most of the ore body and other hydrothermally altered rocks. The oldest rock is the quartz monzonite, cut in an extremely irregular manner by the monzonite porphyry. In the eastern part of the deposit the porphyry forms

the bulk of the rock, but quartz monzonite is present at depth, indicating a probable sheetlike mass of porphyry and possibly a main stock or other source lying still farther east. There is no consistent difference in copper content between the quartz monzonite and monzonite porphyry (pls. 10-17).

Small dikes and irregular masses of diabase cut the quartz monzonite and monzonite porphyry and contain about the same percentage of copper. Other relatively small dikes and irregular intruded bodies are rhyolite that is post-mineral, although some copper may have migrated into it during oxidation in the zone of weathering. Two dikes of rhyolite were cut by shaft 2, and samples of the walls prove that this rhyolite is barren. The amount of contamination, as determined by drilling through thin bodies of rhyolite, appears to be about 0.2 percent copper.

EXPLORATION

The general history of the discovery of the ore body has been given, but a more detailed explanation of methods of exploration may be found in Chapman (1947) and by Steele and Rubly (1947).

The designation of the holes is somewhat confusing. The drill holes on San Manuel Copper Corporation ground designated 1 to 17 were drilled by the Bureau of Mines, and the rest, A to Z and 44 to 106, were drilled by the San Manuel Copper Corporation. At a few places difficulty in drilling forced the abandonment of a hole before it reached its objective; a new hole was then started within a few feet and given the same number or letter with a subnumber, thus 80₁. Some of the original holes drilled by the Bureau of Mines were deepened by the corporation.

The drill holes of the Houghton Group are shown on the maps in this report with a prefix of H. The Bureau of Mines-San Manuel Copper Corporation program involved 105 churn-drill holes and one rotary hole (no. 59). The Houghton Group's exploration consists of 17 holes, mainly churn-drill holes, but a diamond drill was used in the bottom of one of the holes.

Total footage of the Bureau of Mines-San Manuel Corporation churn-drilling program was 198,531 feet and of the Houghton Group 27,908 feet.

At the beginning of the drilling program the Bureau of Mines laid out a drill grid coordinate system with the long axis in a direction N. 60°10' E. This direction was chosen because the diabase dike at the outcrop seemed to limit the ore on the north, and the copper-bearing ground was presumed to extend in the general direction of the dike (pl. 1). Actually, the diabase dike is not known to extend far, and it limits the ore only locally. Nevertheless, the grid, as laid out, served remarkably well, and the western tabular-

shaped part of the ore body is nearly parallel to the N. 60°10' E. drill-grid lines. The preliminary holes were not spaced according to a set pattern but were located as dictated by inferences from known geology and the topography. Eventually a pattern was adopted with holes at 400-foot intervals in the east-west direction of the drill grid and 200 feet in a north-south grid direction. This in effect gave a series of cross sections (see various plates). Topography at some places made it undesirable to locate exactly at intersections. In the later drilling, some holes were spaced 400 feet apart in each direction, for it had become evident that the ore body was large and apparently somewhat uniform over a good-sized area. Statistics on the drilling and equipment used and also the general method of computing grade and tonnage have been given by Steele and Rubly (1947, p. 7).

The coordinates, altitude of collar, and total depth of the holes are given in table 4.

TABLE 4.—Drill holes in the San Manuel area, with coordinates, and altitudes and depth, in feet

[San Manuel Copper Corporation coordinates are shown on plate 1 and grid coordinates on plate 7. Holes with subnumbers were drilled at essentially the same site as the original hole that had to be abandoned]

San Manuel Copper Corporation drill holes

[Data supplied by corporation]

| Hole | San Manuel coordinates | | Drill grid coordinates | | Altitude of collar (feet) | Total depth (feet) |
|----------------------|------------------------|-----------|------------------------|------------|---------------------------|--------------------|
| | Latitude | Departure | Latitude | Departure | | |
| 1..... | 10,903.3 | 11,387.5 | 99.2 S. | 402.1 E. | 3,198.3 | 990 |
| 2..... | 10,681.6 | 11,396.0 | 295.8 S. | 299.1 E. | 3,207.6 | 1,140 |
| 3..... | 10,667.3 | 11,170.4 | 195.9 S. | 96.4 E. | 3,266.1 | 1,285 |
| 4..... | 10,880.9 | 11,741.4 | 294.7 S. | 697.9 E. | 3,161.0 | 1,000 |
| 5..... | 11,064.3 | 11,866.3 | 197.8 S. | 897.6 E. | 3,141.4 | 900 |
| 6..... | 10,448.4 | 10,991.3 | 296.7 S. | 168.0 W. | 3,187.2 | 1,405 |
| 7..... | 10,456.8 | 11,411.2 | 498.3 S. | 200.5 E. | 3,233.3 | 1,420 |
| 8..... | 11,164.3 | 12,040.3 | 197.6 S. | 1,098.2 E. | 3,123.2 | 725 |
| 9..... | 11,425.2 | 11,081.0 | 506.1 N. | 395.9 E. | 3,209.6 | 730 |
| 10..... | 10,229.5 | 10,618.4 | 301.1 S. | 600.3 W. | 3,307.3 | 1,395 |
| 11..... | 10,936.3 | 11,251.2 | 2.8 S. | 300.3 E. | 3,170.2 | 790 |
| 12..... | 10,381.6 | 11,684.0 | 699.3 S. | 399.7 E. | 3,165.3 | 1,590 |
| 13..... | 10,032.8 | 10,271.3 | 299.0 S. | 999.2 W. | 3,219.1 | 1,075 |
| 14..... | 10,754.4 | 11,927.3 | 497.0 S. | 796.2 E. | 3,143.7 | 1,184 |
| 15..... | 9,982.3 | 10,977.8 | 694.2 S. | 411.5 W. | 3,232.7 | 1,990 |
| 16..... | 11,499.3 | 12,426.2 | 99.0 S. | 1,599.7 E. | 3,127.4 | 1,220 |
| 17..... | 10,955.6 | 12,278.4 | 497.1 S. | 1,200.9 E. | 3,135.5 | 1,444 |
| A..... | 10,407.7 | 10,516.7 | 95.9 S. | 599.9 W. | 3,309.7 | 1,215 |
| B..... | 10,257.6 | 11,063.2 | 498.0 S. | 200.6 W. | 3,207.1 | 1,570 |
| C..... | 10,592.9 | 10,440.9 | 102.5 N. | 573.5 W. | 3,294.9 | 940 |
| D..... | 10,059.4 | 10,716.6 | 497.5 S. | 599.8 W. | 3,275.4 | 1,675 |
| E..... | 11,271.5 | 10,020.3 | 900.4 N. | 600.6 W. | 3,373.1 | 500 |
| F..... | 11,302.3 | 12,078.6 | 96.9 S. | 1,200.1 E. | 3,101.0 | 1,095 |
| G..... | 9,712.5 | 10,914.5 | 896.8 S. | 600.8 W. | 3,203.6 | 2,165 |
| H..... | 9,365.9 | 11,112.3 | 1,295.9 S. | 601.6 W. | 3,157.3 | 1,235 |
| H ₁ | 9,359.1 | 11,129.0 | 1,310.1 S. | 590.5 W. | 3,157.2 | 1,265 |
| H ₂ | 9,356.5 | 11,144.1 | 1,319.9 S. | 578.7 W. | 3,156.5 | 2,663 |
| I..... | 9,862.6 | 10,367.6 | 494.6 S. | 1,000.4 W. | 3,240.0 | 1,785 |
| J..... | 10,581.1 | 10,820.3 | 96.5 S. | 250.2 W. | 3,207.9 | 1,240 |
| K..... | 10,208.3 | 10,169.1 | 95.8 S. | 1,000.6 W. | 3,261.0 | 1,229 |
| L..... | 9,834.4 | 9,926.2 | 299.4 S. | 1,397.3 W. | 3,314.9 | 1,560 |
| M..... | 10,284.6 | 11,509.8 | 696.8 S. | 200.3 E. | 3,210.2 | 1,692 |
| N..... | 10,566.7 | 9,964.3 | 308.2 N. | 1,004.9 W. | 3,298.0 | 1,000 |
| O..... | 9,663.3 | 10,023.1 | 496.0 S. | 1,398.4 W. | 3,269.4 | 1,790 |
| P..... | 9,908.0 | 11,262.8 | 900.6 S. | 201.3 W. | 3,207.1 | 2,252 |

TABLE 4.—Drill holes in the San Manuel area, with coordinates and altitudes and depth, in feet—Continued

San Manuel Copper Corporation drill holes—Continued

[Data supplied by corporation]

| Hole | San Manuel coordinates | | Drill grid coordinates | | Altitude of collar (feet) | Total depth (feet) |
|-----------------------|------------------------|-----------|------------------------|-------------|---------------------------|--------------------|
| | Latitude | Departure | Latitude | Departure | | |
| Q..... | 9,686.0 | 10,470.9 | 699.1 S. | 998.7 W. | 3,233.8 | 2,200 |
| R..... | 10,380.2 | 10,074.9 | 100.1 N. | 996.8 W. | 3,255.8 | 755 |
| S..... | 10,005.0 | 9,824.2 | 100.6 S. | 1,400.9 W. | 3,324.4 | 1,275 |
| T..... | 9,807.8 | 9,478.4 | 99.6 S. | 1,799.0 W. | 3,330.6 | 1,173 |
| U..... | 9,507.9 | 10,570.1 | 90.29 S. | 1,001.2 W. | 3,190.6 | 1,030 |
| U ₁ | 9,508.4 | 10,551.4 | 893.2 S. | 1,017.2 W. | 3,190.6 | 2,195 |
| V..... | 9,634.6 | 9,579.3 | 300.1 S. | 1,797.6 W. | 3,278.1 | 1,683 |
| W..... | 11,002.0 | 11,560.1 | 99.5 S. | 600.9 E. | 3,143.7 | 890 |
| X..... | 9,461.3 | 9,675.2 | 498.1 S. | 1,800.7 W. | 3,286.9 | 1,772 |
| Y..... | 9,486.3 | 10,122.8 | 699.1 S. | 1,400.0 W. | 3,221.9 | 2,170 |
| Z..... | 10,108.2 | 11,610.6 | 899.9 S. | 200.0 E. | 3,186.1 | 1,911 |
| 44..... | 11,351.3 | 12,973.2 | 499.6 S. | 2,000.5 E. | 3,147.5 | 1,745 |
| 45..... | 9,535.4 | 11,016.3 | 1,101.0 S. | 600.5 W. | 3,169.4 | 2,333 |
| 46..... | 9,433.8 | 9,228.4 | 299.7 S. | 2,202.0 W. | 3,296.7 | 1,657 |
| 47..... | 9,260.5 | 9,328.9 | 499.9 S. | 2,201.0 W. | 3,345.2 | 1,075 |
| 47 ₁ | 9,257.9 | 9,317.6 | 496.6 S. | 2,212.1 W. | 3,345.4 | 1,670 |
| 48..... | 9,734.5 | 11,362.0 | 1,100.3 S. | 201.6 W. | 3,200.9 | 2,335 |
| 49..... | 9,337.1 | 10,667.2 | 1,099.4 S. | 1,002.0 W. | 3,236.7 | 2,600 |
| 50..... | 11,276.6 | 13,246.0 | 700.1 S. | 2,200.0 E. | 3,150.0 | 1,937 |
| 51..... | 9,935.7 | 11,709.9 | 1,098.9 S. | 200.3 E. | 3,148.1 | 2,024 |
| 52..... | 11,532.4 | 12,873.9 | 300.9 S. | 1,999.9 E. | 3,183.8 | 1,744 |
| 53..... | 9,311.9 | 10,226.6 | 900.1 S. | 1,400.2 W. | 3,263.4 | 2,354 |
| 54..... | 9,235.9 | 8,883.0 | 299.5 S. | 2,600.0 W. | 3,362.2 | 1,439 |
| 55..... | 10,308.0 | 11,958.7 | 899.8 S. | 601.4 E. | 3,143.2 | 1,777 |
| 56..... | 10,793.6 | 11,217.7 | 109.9 S. | 200.1 E. | 3,220.9 | 1,070 |
| 57..... | 9,761.2 | 11,809.4 | 1,299.8 S. | 199.8 E. | 3,148.3 | 2,519 |
| 58..... | 11,196.8 | 13,517.6 | 904.5 S. | 2,395.9 E. | 3,092.9 | 1,915 |
| 59..... | 9,883.5 | 10,817.4 | 700.2 S. | 599.8 W. | 3,223.5 | 1,698 |
| 60..... | 9,113.7 | 9,875.0 | 899.1 S. | 1,800.3 W. | 3,290.2 | 2,300 |
| 61..... | 9,959.9 | 12,156.4 | 1,300.1 S. | 599.6 E. | 3,130.0 | 777 |
| 61 ₁ | 9,966.2 | 12,137.8 | 1,285.4 S. | 586.7 E. | 3,131.2 | 2,075 |
| 62..... | 11,076.3 | 11,287.2 | 100.7 N. | 401.1 E. | 3,147.7 | 818 |
| 63..... | 10,506.3 | 12,304.3 | 899.7 S. | 999.9 E. | 3,125.2 | 1,795 |
| 64..... | 10,159.3 | 12,503.7 | 1,300.0 S. | 1,000.2 E. | 3,082.3 | 2,035 |
| 65..... | 10,705.2 | 12,651.8 | 900.1 S. | 1,402.2 E. | 3,086.2 | 1,835 |
| 66..... | 10,990.8 | 11,096.0 | 121.7 N. | 192.7 E. | 3,217.2 | 1,070 |
| 67..... | 10,873.0 | 9,327.0 | 899.7 N. | 1,400.3 W. | 3,345.9 | 976 |
| 68..... | 9,164.8 | 10,768.4 | 1,299.2 S. | 1,000.0 W. | 3,232.4 | 2,575 |
| 69..... | 9,562.1 | 11,463.0 | 1,300.2 S. | 1,999.8 W. | 3,166.8 | 2,653 |
| 70..... | 10,904.9 | 10,931.0 | 129.3 S. | 6.0 E. | 3,238.9 | 1,673 |
| 71..... | 10,874.1 | 13,026.0 | 939.8 S. | 1,808.9 E. | 3,056.0 | 2,017 |
| 72..... | 10,951.5 | 13,891.1 | 1,302.9 S. | 2,597.8 E. | 3,068.9 | 1,935 |
| 73..... | 10,358.2 | 12,850.9 | 1,300.1 S. | 1,400.2 E. | 3,066.7 | 825 |
| 73 ₁ | 10,326.7 | 12,853.3 | 1,328.6 S. | 1,386.7 E. | 3,068.3 | 1,155 |
| 73 ₂ | 10,342.7 | 12,859.8 | 1,318.1 S. | 1,400.3 E. | 3,067.7 | 2,295 |
| 74..... | 8,914.9 | 9,529.9 | 899.9 S. | 2,198.6 W. | 3,269.4 | 2,115 |
| 75..... | 11,213.1 | 11,438.9 | 144.0 N. | 600.8 E. | 3,168.1 | 710 |
| 76..... | 8,965.1 | 10,421.9 | 1,300.0 S. | 1,399.9 W. | 3,194.2 | 2,725 |
| 77..... | 11,366.2 | 11,792.4 | 100.8 N. | 983.6 E. | 3,137.9 | 1,000 |
| 78..... | 11,041.8 | 13,234.8 | 898.1 S. | 2,073.4 E. | 3,061.3 | 2,170 |
| 79..... | 11,449.65 | 13,146.46 | 500.31 S. | 2,199.69 E. | 3,188.68 | 1,890 |
| 80..... | 9,413.7 | 12,008.4 | 1,700.3 S. | 199.5 E. | 3,116.8 | 1,085 |
| 80 ₁ | 9,408.9 | 11,998.1 | 1,699.3 S. | 188.2 E. | 3,116.9 | 2,635 |
| 81..... | 9,613.0 | 12,354.0 | 1,699.3 S. | 598.4 E. | 3,100.7 | 1,135 |
| 82..... | 8,713.8 | 9,180.5 | 900.4 S. | 2,601.7 W. | 3,315.0 | 2,110 |
| 83..... | 10,555.6 | 13,198.3 | 1,301.7 S. | 1,799.9 E. | 3,052.9 | 2,150 |
| 84..... | 10,575.6 | 13,544.3 | 1,298.7 S. | 2,200.5 E. | 3,034.6 | 2,270 |
| 85..... | 11,251.1 | 12,800.1 | 500.4 S. | 1,800.5 E. | 3,115.1 | 1,605 |
| 86..... | 7,627.8 | 8,884.8 | 1,695.3 S. | 3,398.5 W. | 3,276.9 | 2,850 |
| 87..... | 9,813.2 | 12,701.5 | 1,698.6 S. | 999.5 E. | 3,089.9 | 2,138 |
| 88..... | 10,621.7 | 14,114.0 | 1,700.0 S. | 2,627.1 E. | 3,014.9 | 2,095 |
| 89..... | 10,210.1 | 13,395.7 | 1,699.7 S. | 1,799.2 E. | 3,087.4 | 2,265 |
| 90..... | 9,616.5 | 11,313.4 | 1,699.1 S. | 600.9 W. | 3,144.7 | 2,750 |
| 91..... | 9,564.7 | 13,073.8 | 2,099.3 S. | 1,198.8 E. | 3,104.0 | 2,564 |
| 92..... | 9,962.7 | 13,769.1 | 2,100.04 S. | 1,999.98 E. | 3,072.0 | 2,280 |
| 93..... | 9,614.9 | 13,969.0 | 2,501.2 S. | 2,000.3 E. | 3,017.2 | 2,161 |
| 94..... | 9,267.9 | 14,172.0 | 2,903.3 S. | 2,003.8 E. | 3,033.8 | 2,075 |
| 95..... | 9,217.5 | 13,274.0 | 2,500.2 S. | 1,199.7 E. | 3,137.1 | 2,490 |
| 96..... | 10,161.3 | 14,115.7 | 2,100.3 S. | 2,399.4 E. | 3,062.3 | 2,100 |

TABLE 4.—Drill holes in the San Manuel area, with coordinates, and altitudes and depth, in feet—Continued

San Manuel Copper Corporation drill holes—Continued

[Data supplied by corporation]

| Hole | San Manuel coordinates | | Drill grid coordinates | | Altitude of collar (feet) | Total depth (feet) |
|----------|------------------------|-----------|------------------------|------------|---------------------------|--------------------|
| | Latitude | Departure | Latitude | Departure | | |
| 97..... | 9,365.1 | 12,727.3 | 2,100.1 S. | 798.9 E. | 3,116.2 | 2,485 |
| 98..... | 9,765.8 | 13,421.1 | 2,097.7 S. | 1,600.2 E. | 3,061.0 | 2,296 |
| 99..... | 9,018.8 | 12,926.4 | 2,499.6 S. | 799.4 E. | 3,154.3 | 2,498 |
| 100..... | 8,214.6 | 13,390.0 | 3,427.8 S. | 801.4 E. | 3,182.6 | 2,500 |
| 101..... | 10,011.8 | 13,049.9 | 1,699.6 S. | 1,400.5 E. | 3,088.0 | 2,408 |
| 102..... | 9,167.2 | 12,380.6 | 2,099.3 S. | 399.4 E. | 3,126.3 | 2,755 |
| 103..... | 10,409.1 | 13,743.6 | 1,700.1 S. | 2,200.0 E. | 3,040.7 | 1,105 |
| 104..... | 8,681.3 | 13,121.8 | 2,889.5 S. | 801.0 E. | 3,119.5 | 2,385 |
| 105..... | 8,820.2 | 12,578.3 | 2,498.7 S. | 398.6 E. | 3,190.0 | 1,015 |
| 105..... | 8,822.9 | 12,556.5 | 2,485.4 S. | 381.0 E. | 3,189.8 | 2,635 |
| 106..... | 8,276.6 | 10,026.1 | 1,700.3 S. | 2,085.8 W. | 3,222.5 | 2,595 |
| Shaft: | | | | | | |
| 1..... | 11,700.0 | 9,750.0 | 1,445.0 N. | 685.0 W. | 3,340.2 | 1,650 |
| 2..... | 8,907.8 | 12,618.5 | 2,441.0 S. | 477.0 E. | 3,185.5 | 2,068 |

Houghton Group drill holes

[Data supplied with permission of Tom Lyon]

| | | | | | | |
|---------|----------|----------|------------|------------|---------|-------|
| 1..... | 12,441.4 | 13,774.7 | 47.3 N. | 3,238.1 E. | 3,072.8 | 1,055 |
| 2..... | 10,480.9 | 14,971.7 | 2,248.9 S. | 3,300.9 E. | 3,045.2 | 1,300 |
| 3..... | 12,204.3 | 13,359.0 | 48.4 N. | 2,759.5 E. | 3,089.3 | 1,340 |
| 4..... | 11,777.6 | 13,745.7 | 514.1 S. | 2,882.6 E. | 3,073.1 | 1,870 |
| 5..... | 11,013.8 | 14,474.4 | 1,539.1 S. | 3,134.8 E. | 2,997.9 | 1,724 |
| 6..... | 11,313.5 | 15,017.5 | 1,549.3 S. | 3,755.1 E. | 2,984.8 | 1,405 |
| 7..... | 11,381.9 | 14,133.6 | 1,050.3 S. | 3,022.3 E. | 3,097.7 | 1,480 |
| 8..... | 10,878.7 | 15,014.5 | 1,925.1 S. | 3,536.1 E. | 3,005.4 | 1,855 |
| 9..... | 11,714.1 | 14,943.3 | 1,165.0 S. | 3,889.9 E. | 2,995.0 | 1,820 |
| 10..... | 12,173.3 | 14,807.3 | 699.0 S. | 4,000.4 E. | 3,031.0 | 1,555 |
| 11..... | 11,851.2 | 15,452.7 | 1,299.6 S. | 4,400.1 E. | 2,990.9 | 1,845 |
| 13..... | 11,402.4 | 14,670.8 | 1,299.9 S. | 3,498.4 E. | 3,026.4 | 1,705 |
| 14..... | 11,624.6 | 14,657.9 | 1,100.7 S. | 3,597.8 E. | 3,008.2 | 1,640 |
| 15..... | 11,699.4 | 14,386.0 | 900.5 S. | 3,999.2 E. | 3,018.4 | 1,687 |
| 16..... | 10,908.2 | 14,611.1 | 1,698.9 S. | 3,200.8 E. | 2,994.1 | 1,820 |
| 17..... | 11,255.4 | 14,412.6 | 1,298.9 S. | 3,201.3 E. | 3,047.0 | 1,807 |
| 18..... | 10,646.2 | 14,759.8 | 2,000.1 S. | 3,199.4 E. | 3,011.2 | 2,000 |

SIZE AND SHAPE

The outline of the ore body has not been completely determined by drilling, but its known length is 6,800 feet. Its greatest width is unknown, but drilling in the eastern area revealed ore through a maximum width of more than 3,000 feet. The greatest depth of drilling at the east end was 2,755 feet, but it is reasonably certain that some ore exists below that depth.

To define the ore body, it is necessary to adopt an arbitrary figure for its copper content because the content diminishes above and below the ore body except where the ore crops out or where it contacts the conglomerate. The San Manuel Copper Corporation classified as ore only those rocks having a copper content of 0.5 percent or more, and data in this report are based on this figure as it applies to the entire deposit. Conditions at the time of mining will necessarily deter-

mine where the rock becomes unprofitable as it grades into lean material.

All references to specific tonnages are taken from published company reports.

The cross sections of the western part of the ore body (pls. 9I, J, K, L, and 10-17) show a generally tabular ore body dipping southeast with a footwall of hydromica-pyrite rock and a hanging wall of marginal biotite rock. To the east, however, the deposit expands in width, particularly at depth; and the copper-bearing zone swings around to the south, making it hook-shaped, as shown by the generalized horizontal outline (fig. 8). The sections also give many details of this part of the ore body (pls. 9A, F, H, 13-17). No drilling has been carried on directly west of shaft 2, and further drilling or underground exploration will probably add to the known ore especially to the west and southwest.

The shape of the ore body as it is now understood is difficult to describe, as can be seen by a study of sections through the mineralized mass.

RELATION TO ROCK FORMATIONS

The copper ore consists of mineralized quartz monzonite, monzonite porphyry, and a minor amount of diabase, with little distinction in grade between the different kinds of rock that have undergone similar hydrothermal alteration.

In studying the relation of copper content to the various rocks, an assay graph was plotted to the right of the graphic log of the drill hole. This was done for all holes, and a few logs are shown on the large-scale cross sections (pls. 10-17). It may be observed that the copper content shows no consistent variation in passing from quartz monzonite to monzonite porphyry or diabase; but where rhyolite is present the copper content always drops, and the amounts shown by assays are believed to represent the copper minerals carried down in the hole or knocked off from above by the drill. Anyone interested in checking the detailed relation of individual 5-foot assay values to the various rocks will find complete data on holes 1 to 17, and A to D, in U. S. Bureau of Mines Report of Investigations 4108, pages 20 to 93, August 1947.

To show how little the copper content of the ore changes with varieties of rock, the following tabulation lists adjacent footages of different rock within the primary ore zone and the average copper content for each:

| Hole | Depth (feet) | Kind of rock | Percent copper |
|--------|--------------|-------------------------|----------------|
| I..... | 1,230-1,330 | Quartz monzonite..... | 0.833 |
| | 1,330-1,385 | Monzonite porphyry..... | .895 |
| | 1,385-1,485 | Quartz monzonite..... | 1.032 |
| Z..... | 1,380-1,480 | Monzonite porphyry..... | .714 |
| | 1,480-1,580 | Quartz monzonite..... | .922 |

| Hole | Depth (feet) | Kind of rock | Percent copper |
|------|---------------|--------------------|----------------|
| 471 | 1, 270-1, 320 | Quartz monzonite | 0. 767 |
| | 1, 320-1, 370 | Diabase | . 636 |
| 64 | 1, 680-1, 730 | Monzonite porphyry | . 738 |
| | 1, 730-1, 740 | Quartz monzonite | . 74 |
| | 1, 740-1, 750 | Mixed | . 645 |
| | 1, 750-1, 775 | Monzonite porphyry | . 64 |
| | 1, 775-1, 780 | Mixed | . 68 |
| 72 | 1, 780-1, 830 | Quartz monzonite | . 798 |
| | 1, 720-1, 770 | Quartz monzonite | . 84 |
| | 1, 770-1, 820 | Monzonite porphyry | 1. 042 |
| 801 | 1, 910-1, 975 | Quartz monzonite | . 94 |
| | 1, 975-1, 995 | Mixed | . 946 |
| | 1, 995-2, 065 | Monzonite porphyry | . 84 |
| | 2, 065-2, 115 | Quartz monzonite | . 944 |
| 84 | 1, 700-1, 800 | Monzonite porphyry | . 599 |
| | 1, 800-1, 905 | Quartz monzonite | . 668 |
| 92 | 1, 820-1, 920 | Monzonite porphyry | . 895 |
| | 1, 920-2, 020 | Quartz monzonite | . 899 |

In several examples, the copper content of the ore in the quartz monzonite was slightly higher. In thin section somewhat more shattering was noted in the quartz monzonite (pl. 6F), and this may have created slightly better conditions for entrance and deposition by solutions, but the difference is not great enough to be important. Hole 72 shows that 50 feet of monzonite porphyry has a higher content than the 50 feet of quartz monzonite immediately above it. The chemical composition of the two rocks is much the same, and inasmuch as the rocks were all affected by the same metal-bearing solutions, any difference should be a result of difference in structure or texture. This is not unusual. It is well known that other disseminated copper deposits are made up of more than one variety of rock. Ransome (1919, p. 150) states that in the Ray and

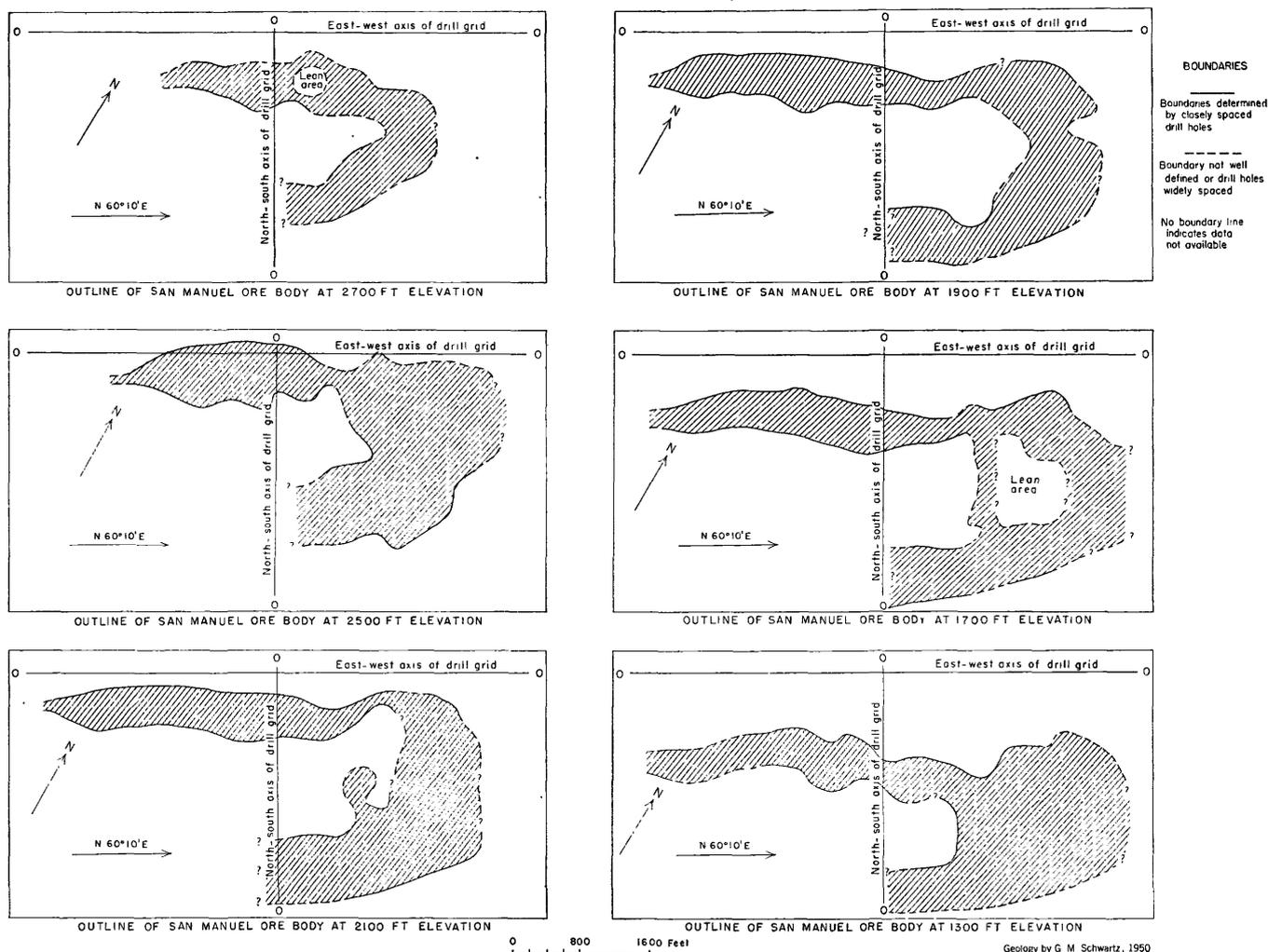


FIGURE 8.—Diagram showing outline of the San Manuel ore body at six altitudes.

Geology by G. M. Schwartz, 1950

Miami districts schist and porphyry have apparently been equally susceptible to metallization, and there is no essential difference between ore in schist and in porphyry.

In the Utah copper mine at Bingham, quartzite bodies in the porphyry are ore bearing in spite of the fact that quartzite is not a particularly favorable host rock.

Of possible significance in the origin of the copper-bearing solutions is the distribution of intruded diabase masses. Small diabase and rhyolite masses are scattered throughout the area of drilling. Inspection of the graphic logs of the holes shows no consistency in the occurrence of either diabase or rhyolite (pls. 10-17). Both occur in quartz monzonite and monzonite porphyry, and at a few places rhyolite or diabase occurs between porphyry and quartz monzonite.

The following abstract from the log of hole 60 is an example of the alternation of the four rock types.

Part of log of hole 60: drill grid coordinates 899.1 S., 1800.3 W.
Depth (feet):

| | |
|-------------|--|
| 1,650-1,895 | Quartz monzonite. |
| 1,895-1,900 | Quartz monzonite and monzonite porphyry. |
| 1,900-1,905 | Monzonite porphyry. |
| 1,905-1,910 | Monzonite porphyry and rhyolite. |
| 1,910-1,930 | Rhyolite. |
| 1,930-1,935 | Rhyolite and diabase. |
| 1,935-1,960 | Diabase. |
| 1,960-1,975 | Quartz monzonite. |
| 1,975-1,985 | Quartz monzonite and monzonite porphyry. |
| 1,985-2,015 | Monzonite porphyry and diabase. |
| 2,015-2,020 | Quartz monzonite and diabase. |
| 2,020-2,025 | Quartz monzonite. |
| 2,025-2,030 | Quartz monzonite and diabase. |
| 2,030-2,040 | Diabase. |
| 2,040-2,045 | Diabase and rhyolite. |
| 2,045-2,065 | Rhyolite. |
| 2,065-2,070 | Rhyolite and diabase. |
| 2,070-2,075 | Rhyolite. |
| 2,075-2,200 | Diabase. |
| 2,200-2,300 | Quartz monzonite. |

The diabase, hydrothermally altered and mineralized, is preore in age. Hulin (1924, pp. 233-284) has attempted to show that ore is often related to late basic intrusive rocks. At San Manuel, however, the ore shows no restriction to the vicinity of intruded diabase, and many diabase dikes are known over a wide area around San Manuel with no associated ore. The largest amount of diabase in the drill holes occurred in holes 46 and 47 and was all low in copper content.

The relation of copper content to the rock types in any given hole may be misleading unless considered in the light of the general structural relations. For example, hole 55 contains monzonite porphyry from 350 to 1,260 feet and averages only 0.4 percent copper, whereas

quartz monzonite from 1,260 to 1,600 feet averages 1.01 percent copper. The explanation of the difference is not in the kind of rock but in the fact that the top of the secondary sulfide zone is near 1,260 feet and the main sericite-copper zone extends from about 1,260 to 1,600 feet, with primary sulfide from 1,455 feet down. The localization of the ore was doubtless determined by structure and the access which the solutions of the sericite-pyrite-chalcopyrite stage of alteration had to the rock.

OCCURRENCE OF COPPER IN THE CONGLOMERATE

The Gila(?) conglomerate lies directly on the San Manuel ore body and adjacent mineralized rocks. In many places the contact is a fault, but an unconformable contact is the normal relation and presumably exists over the eastern part of the ore body. The conglomerate is essentially barren, and copper is found immediately below the contact. There is no known evidence of the alteration of the conglomerate by hydrothermal solutions. There are, however, some occurrences of copper in the conglomerate at the surface and in drill holes and near hole 80 detrital oxidized ore fragments occur in the conglomerate. Also a pit near the location of hole 16 exposed a contact of chrysocolla-bearing conglomerate and quartz monzonite. A pit and incline west of State Highway 77, 300 feet south of the concrete bridge (pl. 1), shows streaks of chrysocolla along the rude bedding of the conglomerate. It seems reasonable to infer that the copper was carried into the conglomerate by meteoric solutions.

Some copper was found in a few drill holes in the conglomerate immediately above the contact with older mineralized rock. Especially important are holes T and V at S. 100 and S. 300 on the W. 1,800 coordinate of the drill grid. In hole T chrysocolla was noted in the conglomerate from 505 to 645 feet. Assays show that the conglomerate averages 0.78 percent copper, whereas the rock below is actually of lower grade, because of the presence of much postore rhyolite.

Hole V, 200 feet south of T, contained chrysocolla in the conglomerate from 420 to 447 and from 690 to 800 feet, and the zone from 695 to 800 feet averaged 0.66 percent copper. Inspection of the vertical sections constructed through these holes indicates that the base of the conglomerate has an average dip throughout the area, and the nature of the cuttings leaves no doubt that the rock above is conglomerate. Inasmuch as most of the ore is pre-Gila(?) in age, it is difficult to explain ore of this thickness and grade in the conglomerate. It may be detrital in part, and meteoric solutions probably have deposited copper dissolved from ore nearby.

Hole 1 was drilled in the hanging wall of the West fault, and mineralized porphyry occurs at the surface 25 feet west of the hole. It seems evident that copper from the porphyry was carried into the conglomerate during weathering. The conglomerate averages 0.26 percent copper, and the first 50 feet of porphyry below averages 0.85 percent.

Hole 3 penetrates 50 feet of conglomerate in the hanging wall of the San Manuel fault before entering mineralized quartz monzonite. The first 35 feet averages 0.29 percent copper, but the 15 feet immediately above the fault consists of a reddish basic volcanic rock that assayed 2.07 percent copper. This volcanic rock may be older than the Gila(?) conglomerate.

Other holes that showed some copper in the conglomerate include hole 15, with 0.10 percent copper from 365 to 490 feet, and hole 1, with 0.81 percent from 545 to 600 feet.

Some of the first holes drilled were sampled consistently through the conglomerate and on assaying showed only a few hundredths of a percent copper, probably within the expected percent of error due to inevitable contamination.

RELATION TO ROCK ALTERATION

The essential nature of the rock alteration has been rather fully described, and the relation of copper ore to the types of alteration mentioned. The relation of ore to rock alteration is one of the most important features of the deposit because it was not only a guide to past exploration but will continue to be a guide to future exploration in the area. The relation shown at San Manuel should also be a useful guide in prospecting and exploring for other deposits where somewhat similar alteration has occurred.

There are four distinctive types of alteration of the porphyry and quartz monzonite that are closely related and are believed to be the result of one extended period of hydrothermal alteration, perhaps with changes in the character of the solutions both in time and in place.

The extensive development of sericite and the occurrence of copper were verified by the first microscopic studies which showed close association of primary chalcopyrite and abundant coarse-grained sericite. Rocks with low-copper and high-pyrite content are intensely altered, but hydromica and other clay minerals are much more abundant than sericite. Rocks in the upper parts of the southern holes are less altered and contain only small amounts of copper and iron sulfides; the copper content and the degree of alteration fade out very gradually above the tabular part of the copper ore zone (pls. 10-17). It should be emphasized that rock of low-copper content in the hanging wall (south)

invariably shows only moderate alteration, whereas rock of the same copper content in the footwall (north) of the ore zone is highly altered and contains abundant pyrite.

At the footwall the ore grades into waste, the copper content dropping from 0.6 percent or higher to 0.3 percent through a zone typically about 50 feet thick. In hole 72, for example, the copper content graded from 1.19 percent at 1,810 to 1,815 feet to 0.29 percent at 1,865 to 1,870 feet. The gradational zone is rarely less than 25 feet thick and in some holes may decrease gradually through as much as 250 feet, as in hole 51. In the footwall the amount of chalcopyrite decreases and the amount of pyrite increases, but toward the hanging wall chalcopyrite and pyrite fade out together.

These generalizations proved to be useful guides in exploration and in evaluating the results of drilling. Visual inspection of the drill cuttings was useful, but detailed study of thin sections of rock fragments was necessary to determine the true nature of the alteration.

The comparison of San Manuel to other "porphyry copper" deposits has been made in a separate paper (Schwartz, 1947, pp. 319-351). In other deposits it has long been known that copper and sericite are closely related. Exceptions are the importance of orthoclase at Ajo and of biotite in some facies of the alteration at Ely, Nev., and possibly Bingham, Utah. Also at the Castle Dome deposit (Peterson, Gilbert, and Quick, 1946, pp. 820-840) the chalcopyrite zone occupies a part of a zone characterized mainly by clay with moderate quartz-sericite alteration, whereas the intense quartz-sericite alteration coincides with the pyrite zone.

Copper is not important in the kaolinite-alunite or in the pyrite-hydromica types of alteration at San Manuel. This also may be true in some other deposits where the clay minerals are important. For example, the copper deposit at Morenci, Ariz., seems to furnish the best example of argillic alteration, but the copper is probably related to the late sericite that is also abundant.

The general relation of ore to the location of both hypogene and supergene alteration zones was misleading in the first holes, which were located where there was a fairly close relation between the bottom of the oxide zone and the water table; this relation falsely indicated a supergene sulfide zone immediately below the water table and a low grade pyritic primary sulfide zone beneath the zone of enrichment. A heavy cover of conglomerate and deep oxidation (600 to 700 feet) in the first holes made information difficult to obtain. Thin sections, however, showed the close association of copper and sericite. Hole 15 was eventually drilled farther out in the hanging wall, and J. H. Hedges, district engineer, Bureau of Mines, wisely decided to

extend the hole at depth. The results gave an accurate picture of a dipping tabular ore body that extended through the entire central and western part of the ore body (west of the 800 E. line on the drill grid, pl. 9J, L). The zones in this important hole may be summarized as follows:

Log of churn-drill hole 15; drill grid coordinates 694.2 S., 411.5 W

| | |
|-------------|---|
| 0-365 | Gila(?) conglomerate. |
| 365-1,300 | Marginal biotite rock, partly oxidized, varies from dark gray to buff. Average copper content 0.328 percent. Typical fringe zone alteration. Mixed monzonite porphyry and quartz monzonite. |
| 1,300-1,380 | Partly oxidized secondary sulfide ore. Moderate alteration. Average copper content 0.545 percent. |
| 1,380-1,475 | Zone of secondary enrichment. Moderately altered quartz monzonite. Average copper content 0.84 percent. |
| 1,475-1,945 | Primary sulfide zone. Sericitized quartz monzonite with pyrite and chalcopyrite. Typical ore-zone alteration of quartz monzonite. Average copper content 0.90 percent. |
| 1,945-1,990 | Primary sulfide with high-pyrite content; gradation to pyrite-hydromica type of alteration. Average copper content 0.432 percent. |

The upper part of the hole shows about 1,000 feet of rock that is representative of the marginal biotite alteration, then a zone of sericitic alteration typical of the copper-bearing zone, which in turn grades downward to the pyritic zone. It should be noted that the greater part of the ore is primary, having average copper content slightly greater than the enriched ore above, which was formed in the relatively lean hanging-wall rock.

GROUND WATER

Ground-water conditions bear important relation to the geology of the deposit and to the mining of the ore.

The water table lies at a considerable depth, as it does throughout much of the desert area of southern Arizona. Because of the variable permeability of the rock and the fact that water was introduced during churn drilling, it is to be expected that determination of water levels in the holes after completion is not entirely consistent. Caving frequently causes abnormal levels. It seems wise to discount somewhat any measurements that depart radically from levels nearby.

The available measurements show that the water table ranges from altitudes of 2,450 to 2,950 feet, corresponding to depths of 300 to 800 feet beneath the surface. The most common depths are between 500 and 600 feet. Systematic measurements by the San Manuel Copper Corporation engineers at monthly intervals from June 1946 to May 1947 show considerable

fluctuation. Some levels were higher in May 1947 than in June 1946, and about an equal number were lower. The variation in most holes was a few feet, but a small number varied from 40 to 100 feet. It was found that the 7 holes that showed less than 10 feet of variation from June 1946 to May 1947 all showed a rise. With the sinking of two shafts on the property, the water levels have been greatly affected, and continuous change may be expected as sinking and drifting are carried on.

The levels, as determined from June 1946 to May 1947, often differ considerably from the point at which water was first noted in drilling. Fissures carrying water might give an entirely erroneous idea of the water table as judged during drilling.

In a general way the water level in the drill holes is high at the west end of the drill grid and low at the east end; that is, varying from high to low in a direction N. 60° E. For example, the altitude of the water level in July 1946 along drill grid coordinate S. 300 varied as follows from west to east: hole 54—2,972 feet, hole 46—2,830, hole V—2,686, hole L—2,782, hole 10—2,627, hole 3—2,572, and hole 52—2,532 feet. The slope averages 300 feet within the distance of 4,600 feet between holes 54 and 52. It is significant that the altitude of the collar of hole 54 is 3,362 feet and that of hole 52 is 3,183 feet, conforming with the general slope of the area toward the San Pedro River. The controlling factor in the water table of the region is no doubt the San Pedro River, which is the master stream of an area extending from the Mexican border west of Bisbee, to its junction with the Gila River near Winkelman, 20 miles north of the San Manuel area. The altitude of the San Pedro River, at Mammoth, about 2,330 feet, is 200 feet below the water level in hole 52. The distance from hole 52 to the river is about 2 miles. The San Pedro is an intermittent stream but has a considerable underflow in the alluvial material below the river bed.

The St. Anthony mine has ore developed along well-defined fault fissures or brecciated zones, and it is natural therefore that considerable water should be found. It was reported in 1949 that 2,000 gpm was being pumped from the 1,050-foot level. The original water level was at 2,495 feet above sea level and had been lowered to 2,356 feet in 1945. The following analysis, available through the courtesy of the management of St. Anthony mine, indicates the composition of the mine water:

Partial analysis of water, St. Anthony mine

| | <i>Parts per million</i> |
|--------------------------------|--------------------------|
| Dissolved solids | 522 |
| Calcium (Ca) | 52 |
| Magnesium (Mg) | 4 |
| Bicarbonate (HCO) ₃ | 268 |
| Sodium (Na) | 90 |
| Chlorides (Cl) | 30 |

Partial analysis of water, St. Anthony mine—Continued

| | <i>Parts per million</i> |
|----------------------------------|--------------------------|
| Sulfates (SO ₄)----- | 75 |
| Fluorides (F)----- | 2.8 |

The San Manuel deposit apparently is not localized by well-defined fissures, and less water would be expected unless the faults known to be of later origin than the ore prove to be channels of free circulation. In sinking shaft 2 it was found that rhyolite dikes were prolific sources of water, and fractured ground in shaft 1 also furnished much water. A few drill holes were reported by the drillers to have open crevices or cavities, especially holes 97, 99, and 102. Such areas may be expected to yield considerable water, especially when first opened, but because the rocks are porous only where fractured their retained water should eventually drain out, as it has at the St. Anthony mine.

The holes having only a small fluctuation in static water level between June 1946 and May 1947 may be considered to give the most dependable indication of the true water table in the ore deposit. Holes 3, M, Z, 44, 51, 52, 55, and 60, all showing less than a 10-foot change, indicate a slope along the east-west axis of the drill grid of 156 feet in 3,800 feet, a slope somewhat less than the figure given above. Even this slope would carry the water table well below the level of the San Pedro River at Mammoth, but the gradient is probably flatter in the porous gravels of the alluvial slope deposits and the conglomerate below.

It may be inferred that a considerable source of seepage to ground water is Tucson Wash just west of the San Manuel deposit. This wash heads near Oracle at the north end of the Santa Catalina Mountains, and thus has a considerable drainage area. The bottom of the wash is at an altitude of about 3,000 feet opposite the explored area; this is above the static level in most of the holes at the time they were drilled. In fact, in most holes at the west end water was struck at relatively high altitudes. The generally high static level which has fluctuated rather widely in these holes is a basis for the inference; yet shaft 1, on the east side of Tucson Wash, struck no water when it passed through the level of the wash. This fact indicates that the wash is not generally an important source of ground water. This observation was also borne out by a dry drift of the St. Anthony mine 300 feet under the wash.

HYPOGENE ORE

The present size and shape of the primary (hypogene) sulfide zone have been determined by the modification of the original ore body by oxidation and enrichment, and to some extent by postmineral faulting. Throughout the explored area the primary sulfide zone extends

below the bottom of the deepest drill holes, but in most holes the lower part is highly pyritic and low in copper. The upper surface of the primary sulfide zone is generally in contact with the supergene sulfide zone, but at places highly oxidized material rests directly on primary sulfide. Typical relations of the primary, secondary, and oxidized zones are shown by the sections (pl. 9). At the western end of the explored area the San Manuel fault cuts across the oxide and secondary sulfide zones; so, in hole 47 only 15 feet of slightly oxidized lean ore lies between the primary sulfide zone and the Gila(?) conglomerate above the fault.

The surface of the primary sulfide zone ranges from smooth to irregular in different parts of the area, and great variations in altitude are common. This is shown by plates 9-17. The extremes of depth were found in the drilling of hole E (pl. 9J) where heavy pyritic material was cut at a depth of 285 feet, and of hole 79 (pl. 9C) where predominant secondary sulfide material was first struck at 1,630 feet and primary sulfide at 1,720 feet. In shaft 1, north of hole E, the first sulfide was struck at 130 feet, but oxidation along shear zones occurred for some hundreds of feet below. Possible reasons for such variations will be discussed after the description of the zones of oxidation and enrichment.

The primary copper mineralization, as previously described, has formed a wide, steeply inclined tabular body in the western part, which has been enlarged eastward into an irregular hook-shaped mass with a nearly vertical attitude, at least along the south contact (fig. 8).

The ore consists of disseminated chalcopyrite and pyrite in highly sericitized monzonite porphyry and quartz monzonite with many other hydrothermal alteration products. In the panned concentrates the two minerals have usually broken apart, but inclusions of chalcopyrite in pyrite are common, and pyrite is replaced by chalcopyrite in a few grains (pls. 5A, B). Chalcopyrite in a few grains is intergrown with rutile, indicating essentially contemporaneous formation of the two minerals (pl. 5F). The only other primary copper mineral is bornite, although most bornite is supergene.

A great vertical range of ore, almost entirely primary, exists in places in the east area. For example, hole 92 has 1,515 feet of primary ore between 705 and 2,220 feet that averages 0.9 percent copper (pl. 14). The pyritic zone from 2,220 to 2,280 feet averages 0.29 percent copper. A thick section of primary copper ore is well developed along the 2,500 S. coordinate (pl. 17).

The uniformity of the rock alteration and copper content is remarkable. In the 1,455 feet of hypogene ore in hole 92 between 705 and 2,160 feet that averages

0.9 percent copper content, one 5-foot section assayed 2.66 percent, another 1.88 percent, and the next highest was 1.47 percent. The lowest assay between 705 and 2,150 feet was 0.58 percent. This is, of course, an unusually thick section of ore and somewhat more uniform in content than average. There is also an abrupt transition to pyritic rock to the south where hole 94, only 800 feet away from hole 92, is highly mineralized with pyrite but contains no ore.

The outer, or marginal biotite, alteration affected the hanging-wall rocks of the main mineralized belt. Generally the rock of the primary zone that shows this type of alteration appears fairly fresh, but in thin section the groundmass is a complex of alteration products, including secondary biotite, hydrobiotite, sericite, epidote, zoisite, chlorite, and small amounts of several clay minerals. Plagioclase phenocrysts of the porphyry are considerably altered to sericite, chlorite, and clay minerals. In the area of drilling, this rock consistently carries small amounts of copper. Zero assays are so uncommon as to inspire a special look at the rock cuttings for other unusual features. The persistence of small amounts of pyrite and chalcopyrite in moderately altered rock over large areas suggests the possibility of ore beyond that now known, particularly to the south beneath the cover of conglomerate.

It is clear that the nature of the rock and the copper content in the hypogene sulfide zone vary greatly, depending on which type of alteration took place. A copper content approaching that necessary for ore is always in the highly sericitic rock. To show how the copper content ranges in the three types of altered rock, a compilation from a few deep holes will serve (table 5). These are not necessarily average holes, but were selected because of a thick section in the primary sulfide zone extending from the hanging wall through the ore zone and into the pyritic rock of the footwall. They represent, in fact, below average ore content.

The primary copper zone always contains a considerable amount of pyrite. Study of more than 2,000 sections of mounted and polished concentrates shows that pyrite is the predominant sulfide in almost all parts of the primary zone. The complete analysis of rock from the ore zone in hole I showed 4.97 percent pyrite. Data furnished by the Magma Copper Company's laboratory for selected samples from various holes show a range of pyrite in the ore zone from 1.8 to 5.2 percent. In the pyritic zone the total determined sulfide, mainly pyrite, runs as high as 8.91 percent and is probably higher in some of the holes for which data on pyrite content are not currently available. In the primary copper zone, chalcopyrite ranges from 19 to 62 percent of the total sulfide, probably averaging about 40 percent.

Table 5.—Average copper content of primary mineralized rock in hanging wall, ore zone, and footwall

| Hole | Drill grid coordinates | Depth (feet) | Copper content (percent) | Zone |
|------|--------------------------|--------------|--------------------------|---|
| 45 | 1,101.0 S. 600.5 W. | 590-1,610 | 0.255 | Hanging wall. Copper zone. Footwall. |
| | | 1,610-2,285 | .644 | |
| | | 2,285-2,350 | .237 | |
| 65 | 900.1 S. 1,400.2 E. | 1,540-1,610 | .211 | Hanging wall. Copper zone. Footwall. |
| | | 1,610-1,750 | .603 | |
| | | 1,750-1,886 | .212 | |
| 72 | 1,302.9 S. 2,597.8 E. | 1,450-1,540 | .257 | Hanging wall. Copper zone. Footwall. |
| | | 1,540-1,850 | .736 | |
| | | 1,850-1,965 | .27 | |
| 89 | 1,699.7 S. 1,799.2 E. | 1,100-1,600 | .44 | Hanging wall. Copper zone. Footwall. |
| | | 1,600-2,190 | .79 | |
| | | 2,190-2,265 | .35 | |
| 93 | 2,501.2 S. 2,000.3 E. | 590-900 | .107 | Hanging wall. Intermediate lean zone. Copper zone. Footwall. |
| | | 900-1,390 | .403 | |
| | | 1,390-1,925 | .824 | |
| | | 1,925-2,160 | .154 | |
| 95 | 2,500.2 S. 1,199.7 E. | 685-815 | .266 | Hanging wall. Copper zone. Footwall. |
| | | 815-2,415 | .80 | |
| | | 2,415-2,490 | .281 | |
| 101 | 1,699.6 S. 1,400.5 E. | 1,120-1,830 | .398 | Hanging wall. Copper zone. Footwall. |
| | | 1,830-2,325 | .834 | |
| | | 2,325-2,408 | .137 | |

High-grade zones in the primary ore are few and of moderate value. One of the best examples of a thick section of relatively high-grade ore is in Bureau of Mines hole 15 where the average copper content from 1,515 to 1,625 feet was 1.44 percent copper. As noted above for hole 92, individual assays of primary ore run as high as 2.66 percent for a 5-foot section.

At the footwall the ore grades gradually into waste, the copper content dropping from 0.6 percent or higher to 0.3 percent through a zone typically about 50 feet thick. In hole 72, for example, the copper content graded from 1.19 percent at 1,810 to 1,815 feet to 0.20 percent at 1,865 to 1,870 feet. The gradational zone departs from the average in many holes but is rarely less than 25 feet thick and in some holes may decrease gradually through as much as 250 feet, as in hole 51. In the footwall the amount of pyrite increases, but toward the hanging wall both chalcopyrite and pyrite fade out together.

OXIDIZED ORE

Oxidation (see Schwartz, 1949, for an earlier summary) has been extensive but variable in the ore body and in adjacent mineralized rock, particularly where the pyritic rock was originally at or near the surface. The relation of oxidation to ore varies greatly from place to place, and it is evident that complex structural and other changes in Tertiary and Quaternary time have

resulted in features of the zone of oxidation that are difficult to explain. The better grade oxide ore in many places no doubt represents oxidation of former supergene chalcocite ore. Several of the assay graphs illustrate this fact (pls. 10-17) and hole W is a specific example (pl. 13). The oxidized ore, as calculated with a 0.5 percent cut-off, is, in general, slightly lower in grade than the sulfide ore. This probably is a result of some leaching and downward migration of copper that is known to have taken place because of the chalcocite occurring below. The combination of leaching and enrichment makes the copper content more erratic than in the primary sulfide zone. Hole 56 in the outcrop area is perhaps a good example. Two adjacent 5-foot sections assayed 2.43 and 0.35 percent copper. At places, particularly in the southeast ore body, there is a virtual absence of oxide ore because copper has been extensively leached.

In the tabular mass, characteristic of the western part of the ore body, many holes drilled into the hanging wall of the main copper ore zone pass through long columns of very lean oxidized ore usually containing less than 0.3 percent copper because the primary mineralization was slight (pls. 10 and 16). In parts of this hanging-wall zone the small amount of sulfide present has largely escaped oxidation because the rock was relatively impervious to solutions. In some holes it is actually difficult to determine what footages should be classified as being in the oxide zone. The staff of the San Manuel Copper Corporation has calculated much of the ore in these indefinite zones as mixed sulfide and oxide, an important metallurgical distinction. Geologically, the presence of oxidized ore is important in working out a sequence of events to explain logically conditions as found.

The oxidized part of the deposit varies greatly in thickness, owing to several factors. The thickness of the Gila(?) conglomerate over the deposit ranges from a feather edge to 1,395 feet in hole 86, to the southwest of the deposit. Where a great thickness of conglomerate exists, the oxide zone has usually been largely cut off by faulting, as shown in some of the vertical sections (pl. 15). For example, along the 500 S. coordinate (pl. 9C), the oxide zone is gradually transected to the west by the San Manuel fault; so, essentially no oxide zone remains at the west end. Tilting has doubtless been responsible for preservation of some of the thick parts of the oxide zone. It also seems probable that in places the great depth to the base of the oxide zone is a result of both tilting and down-faulting. Creasey (1950, pp. 63-84) states that oxidation in the Mammoth vein of the St. Anthony mine may have occurred before down-faulting of the ore.

Locally there is much variation vertically in the

amount of oxidation, and zones of high oxidation may be below less oxidized parts. Hole B is an example, as the following tabulation shows:

Log of hole B; drill grid coordinates 498.0 S., 200.6 W.

| Depth (feet) | | Copper content (percent) | Oxide copper (percent) | Percent as oxide |
|--------------|------------------------------------|--------------------------|------------------------|------------------|
| 0-300 | Gila(?) conglomerate..... | | | |
| 300-350 | Rhyolite..... | 0.15 | | |
| 350-445 | Oxidized hanging-wall zone..... | .293 | 0.211 | 72 |
| 445-695 | Oxidized ore zone..... | .532 | .464 | 87 |
| 695-825 | Variable oxidized ore zone..... | .567 | .301 | 53 |
| 825-950 | Partly oxidized enriched zone..... | 1.082 | .416 | 38 |
| 950-1,210 | Oxidized lean enriched zone..... | .672 | .426 | 63 |
| 1,210-1,360 | Secondary sulfide zone..... | 1.04 | .116 | 11 |
| 1,360-1,455 | Primary copper zone..... | .694 | .018 | 2.7 |
| 1,455-1,570 | Primary pyritic zone..... | .28 | .013 | 4.6 |

It is evident from the relatively high-grade ore of a part of the oxide zone that a zone of supergene enrichment has been oxidized. Holes J, 44, 79, and 103 furnish good examples. Some essential facts are brought out by the following tabulation:

Assay data from three drill holes in the oxide zone

| Depth (feet) | Avg. copper content (percent) | Copper as oxide (percent) | Percent as oxide |
|--|-------------------------------|---------------------------|------------------|
| Hole J; drill grid coordinates 96.5 S., 250.2 W. | | | |
| 120-185..... | 0.551 | 0.351 | 63.7 |
| 185-305..... | 1.447 | 1.312 | 90.7 |
| 305-720..... | .722 | .543 | 75.2 |
| Hole 44; drill grid coordinates 499.6 S., 2000.5 E. | | | |
| 155-590..... | 0.227 | 0.10 | 44 |
| 590-735..... | 1.055 | .944 | 89.5 |
| 735-1,385..... | .579 | .420 | 72.5 |
| Hole 79; drill grid coordinates 500.3 S., 2199.6 E. | | | |
| 215-475..... | 0.226 | | |
| 475-950..... | .954 | 0.746 | 78.3 |
| 950-1,630..... | .331 | .153 | 46.2 |
| 1,630-1,710..... | 1.245 | .345 | 27.7 |

In some parts of the deposit there is a striking change in the depth of oxidation; for example, along the 2000 E. coordinate, oxidation is deep in holes 44, 52, and 78, ranging from 1,385 to 1,555 feet, whereas in hole 92, 1,200 feet south of hole 78, the bottom of the oxidized zone is at 665 feet. A similar difference is shown on plate 19 between holes 71 and 89.

In general, it is possible to designate an approximate depth at which the zone of extensive oxidation ends.

This depth ranges from 130 feet (altitude 3,210 feet) in shaft 1 and 285 feet (altitude 3,088 feet) in hole E, which is in the pyritic zone on the southwest slope of Red Hill, to 1,630 feet (altitude 1,558 feet) in hole 79. The shallow occurrences of pyrite are several hundred feet above the water table as shown by drilling, and the deepest oxide is nearly a thousand feet below it. Other holes show a fairly continuous gradation between the two extremes. Some of the holes that show a great thickness of the moderately altered hanging-wall type of rock show no zone of oxidation or secondary sulfide zone in the true sense—for example, holes 53 and 76. Because this rock was fairly impervious and weathering solutions penetrated it only locally, the small amount of sulfide present escaped oxidation. It is probably better not to try to designate zones of oxidation and enrichment under such conditions.

At the outcrop, chrysocolla is the predominant copper mineral of the oxidized zone, as it is throughout the oxidized part of the ore body insofar as the churn-drill cuttings permit one to judge. Locally, malachite and rarely azurite occur, but these minerals seem to account for little of the copper content. Because of the abundance of red iron oxide in the ore, it is difficult to estimate the amount of cuprite. At the bottom of the oxidized zone, where supergene chalcocite has been subjected locally to oxidation, cuprite is fairly common (pls. 4A, 5D). Panning of sludge from all drill holes indicates, however, that cuprite is not abundant at San Manuel. It is probable that the availability of silica prevented much cuprite from forming, although it seems to have formed when the zone of oxidation moved down into chalcocite ore; chrysocolla at places has replaced both cuprite and chalcocite. This is a common process but it is of more than usual importance in a deposit with a complicated history and a variable relation to the water table.

It has been noted that in many holes there does not appear to be enough chrysocolla to account for all of the copper content. It is possible that the copper is partly in cuprite mixed with, and masked by, the prevalent iron oxide. In other deposits rich oxidized copper ore often appears to be merely a mass of iron oxide.

Hundreds of polished sections of concentrates containing iron oxide have been examined under the microscope. The greater part of the iron oxide resulted from the oxidation of pyrite, some doubtless came from chalcopyrite, and a small amount resulted from the oxidation of magnetite. Remnants of pyrite are abundant in some samples (pl. 6D, E).

Lovering (1948, pp. 1–20) has made a study of the thermal gradients in 11 churn-drill holes, with significant results bearing on the present rate of oxidation. A change was found in the heat gradient from about 1.5°

Fahrenheit per 100 feet where sulfides were at or above the water level to about 1° Fahrenheit per 100 feet below the water table. The average gradient both above and below water level in the oxidized ores is 1° Fahrenheit per 100 feet. Using the gradients above and below the deflection as a basis, calculations indicate that about 40,000 years would be required to complete the oxidation of the pyrite in hole 9. This emphasizes the fact, evident from other geologic data, that there is very little oxidation now going on, and the conditions of oxidation and enrichment found are the result of an earlier erosion cycle. Lovering believes that oxidation now is largely due to air entering and leaving voids as a result of changing barometric pressure.

DISPERSION OF COPPER BY WEATHERING

A detailed study has recently been made of the distribution of copper in soils, alluvium, ground water, and vegetation in the San Manuel area (Lovering, Huff, and Almond 1950, pp. 493–514). Some of the more important conclusions from this work may be briefly stated, but the paper should be consulted for the detailed evidence on which these conclusions are based. Samples of underground water from churn-drill holes show that at the present very little copper is going into solution from the deposit, a condition that supports Lovering's conclusions just cited. Much of the copper found in the soil is mechanically eroded and transported chrysocolla. The distance that the copper can be traced depends on the copper concentration in the rock and the amount of dilution by slope wash and tributary gullies. Samples of alluvium more than a mile downstream from the outcrop show slightly more than the average amount of copper in the rock.

Plants growing on the outcrop contain very little copper; however, certain plant species, especially the California poppy, show a marked preference for the outcrop, as was remarkably well shown in the spring of 1945 when relatively good precipitation supported an abundant crop of desert flowers. Other plants that show a preference for the outcrop of oxidized ore are scrub oak and Rothrock grama grass.

Detailed sampling shows a close relation between the type of hydrothermal alteration which has affected the rocks and the type of soil developed on them. The red soil of the hydromica-pyrite zone contains only about 20 ppm of acid-soluble copper, a small fraction of that originally present. Presumably sulfuric acid generated by the weathering of pyrite has removed most of the copper.

Some of the soil over the oxidized zone is as high in copper content as the chalcocite zone which exists at a depth of several hundred feet. An important fact proved by the analyses is the way in which copper-rich

soil creeps down the slope to mix with the soil of the barren Gila(?) conglomerate. Extensive contamination of the alluvium of the gullies and washes by drainage from the cuttings of churn-drill holes was found, as might be expected.

SUPERGENE ENRICHMENT

The downward enrichment of copper in the San Manuel deposit has been extremely variable. Many of the features of enrichment have been previously described (Schwartz, 1949, pp. 253-277). Considered as a whole, the amount of enrichment is not great. The Magma Copper Company in a prospectus dated February 15, 1949, states that there are 123,499,580 tons of oxide ore averaging 0.767 percent copper. Assays show that considerable copper as sulfide remains in some of this ore. The quantity of oxidized ore is a good indication that conditions in general did not favor much solution of copper in the oxide zone and re-deposition of it below the water table. This is not true for the eastern part of the ore body where leaching was extensive and there is very little oxide ore. Any general statement may be misleading when applied to individual drill holes. Some holes show no recognizable zone of supergene enrichment, but the oxide and primary sulfide zones are in contact. A great thickness of slightly mineralized hanging-wall rock overlies the sulfide (pl. 15) where these holes have, in general, been drilled. Holes 76 (pl. 10) and 68 (pl. 11) are good examples. Other holes essentially lacking a zone of enrichment include V, 45, 46, 52, and 54. In some holes both the oxide and supergene sulfide zones have been largely cut off by faulting (pl. 9B, C).

Some drill holes, for example, holes U, 15, 16, and 76, have a supergene sulfide zone, but with such a small amount of chalcocite that there has been little enrichment. Many drill holes along the western part of the ore body show a moderate enrichment by chalcocite, but the average grade is only a few tenths of a percent above that of the primary chalcopyrite-pyrite ore. A detailed study of holes 4, 6, 7, and 10 drilled by the U. S. Bureau of Mines showed a total of 775 feet of drilling in the supergene sulfide zone that averaged 1.03 percent copper. The corresponding primary sulfide zone showed an average of 0.522 percent copper for a total of 500 feet of drilling. This is of lower grade than average primary ore in which many holes show large footages that average 0.8 percent. Generally, because enrichment is not great, the outline of the supergene sulfide zone has been based on the presence of supergene chalcocite rather than on the amount of enrichment in copper content (pls. 9-14).

Holes showing pronounced enrichment are mainly in the eastern part of the deposit, but the supergene

sulfide zone is usually thin in that area. For example, hole 92 near the south edge has 275 feet of conglomerate, and below it 390 feet of oxide zone that averages only 0.1 percent copper. This is believed to have been originally high in pyrite but low in copper. The supergene sulfide zone below the oxide zone is 40 feet thick and averages 1.793 percent copper, but the primary zone averages only 0.877 percent, including pyritic rock at the bottom of the hole. Hole 44 at S. 500, E. 2000 on the drill grid shows unusually high enrichment at a depth of 1,385 to 1,525 feet where the copper content averages 2.08 percent. The primary sulfide ore averages less than one-half percent copper. The highest assay in the enriched zone is 5.64 percent copper. Hole 58 also has a rich secondary zone at a depth of 1,455 to 1,800 feet, averaging 1.57 percent copper. Hole 15 drilled by the Bureau of Mines (Chapman, 1947, p. 65) furnishes a good example of an enriched zone in lean rock which happened to lie just above better grade primary sulfide ore. The following tabulation gives the essential facts:

Zones of hole 15; drill grid coordinates 694.2 S., 411.5 W.

| Depth (feet) | Description |
|--------------|--|
| 0-365 | Gila(?) conglomerate. |
| 365-1,300 | Zone of oxidation, weak mineralization, sulfides locally. Average at 490-1,300 ft., 0.328 percent copper content. |
| 1,300-1,380 | Partly oxidized supergene sulfide. Zone of moderate mineralization. Average copper content 0.545 percent. |
| 1,380-1,415 | Principal zone of supergene enrichment. Average copper content 0.792 percent. |
| 1,415-1,475 | Zone of weak enrichment as shown by microscopic examination of concentrates. Average copper content 0.858 percent. |
| 1,475-1,945 | Primary sulfide zone containing chalcopyrite. Average copper content 0.90 percent. |
| 1,945-1,990 | Primary sulfide zone with high-pyrite content. Average copper content 0.432 percent. |

Proper interpretation of the extreme variability of supergene enrichment depends on a very careful correlation of assay data, including the oxide to sulfide ratio, the mineralogic data obtained by detailed microscopic studies, and the kind of hydrothermal alteration or primary mineralization. The distribution of the supergene sulfide minerals differs from zone to zone. Secondary sulfide forms a thin but well-defined zone in pyritic rock; supergene sulfide is thick in the chalcopyrite rock and fades out gradually below it; but in the hanging-wall zone supergene chalcocite is sporadic and seldom assays 0.5 percent copper although it may exist through a thickness as great as 200 feet.

In a series of holes, variations in grade of the supergene sulfide minerals are often readily explained by the differences in the primary mineralization (pls. 15 and 16). In the pyritic zone, a good precipitant of chalcocite was

available, and the amount of chalcocite depended on the copper available from above because there was little in the primary pyrite. Hole C is a good example of enrichment in the pyritic zone. The location of this hole indicates that the copper content of the primary sulfide was low, probably about 0.2 or 0.3 percent. Drilling has revealed the following copper content of zones:

Zones of hole C; drill grid coordinates 102.5 N., 573.5 W.

| Depth (feet) | | Copper content (percent) |
|--------------|--|--------------------------|
| 0-210 | Gila(?) conglomerate. | |
| 210-640 | Zone of oxidation | 0.375 |
| 640-710 | Mixed oxide and supergene sulfide zone | .366 |
| 710-725 | Zone of supergene sulfide enrichment | 1.156 |
| 725-800 | Zone of slight enrichment | .505 |
| 800-940 | Hypogene sulfide zone | .24 |

Microscopic study of mounted panned concentrates from hole C shows an abundance of iron oxide and a little pyrite and chalcocite from 640 to 700 feet. From 700 to 725 feet chalcocite and pyrite are abundant, but below 725 feet pyrite and variable iron oxide constitute most of the samples. In the richer zones chalcocite extensively replaces pyrite grains, leaving pyrite remnants. Chalcopyrite is scarce or absent throughout, and there is little doubt that a copper content above 0.3 percent is a result of supergene enrichment, probably from rock removed by erosion previous to deposition of the conglomerate.

In the sericite-pyrite-chalcopyrite zone, a fair amount of copper was originally present, and chalcopyrite and pyrite were good precipitants of chalcocite. Moderate enrichment thus resulted in good ore. In the hanging-wall zone, the rock was comparatively tight, mineralization was slight, and not much copper was available; solutions had trouble getting through from above, and there was a lack of chalcopyrite and pyrite to act as precipitants. Under these conditions supergene sulfide zones contain little copper. The cross sections show several good examples.

One of the striking features of the San Manuel deposit is the abrupt change in altitude of the zone of secondary enrichment. At places there is a steep dip to the zone of enrichment, as is shown by the cross section along the 600 W. and 1,000 W. drill grid coordinates (pls. 9J and 11). At 1,000 W., hole R at the north end shows the top of the secondary sulfide zone at 360 feet, whereas in hole 68 at the south end it is at a depth of 2,000 feet. At other places the displacement appears to be abrupt, as along the 1,000 E. coordinate (pl. 9N) and the 1,800 E. coordinate (pls. 9O and 14). This would appear to be easily explained by faulting, but the contact of the ore zone and the pyritic footwall does not appear to be displaced and therefore a fault is unlikely (pls. 13 and 14). At places it is believed that there is a moderate displacement of the zone of enrich-

ment as well as other zones, as is indicated on the section along the 100 S. and 500 S. coordinates (pl. 9B,C).

The detailed information available about oxidation and enrichment in the San Manuel deposit permits some comparison with other disseminated copper deposits. The presence of a very large amount of oxidized ore (123,499,588 tons) is similar to the upper part of the New Cornelia ore body at Ajo, Ariz., where copper carbonate and silicate formed about 25,000,000 tons of ore. There is an abrupt transition to practically unaltered primary ore below. Gilluly (1946, p. 86) believes the lack of leaching and secondary enrichment may be accounted for by the small amount of pyrite in the part of the ore body exposed in the Recent cycle of weathering. There is little doubt that this explanation applies to part of the San Manuel deposit, although the possibility that a desert climate may have had an effect is recognized for both deposits.

In contrast to the condition just described, the ore of the large disseminated deposit at Morenci is all a result of secondary sulfide enrichment. The protore is very low grade pyritic rock; so, large amounts of copper must have been carried down from rock now removed by erosion, as well as from the leached capping.

In the southeast part of the ore body at San Manuel it seems clear that abundant pyrite, in what is now a leached zone, furnished sulfuric acid to dissolve the copper and carry it down to form the rich chalcocite zone, described in association with hole 92, where 390 feet of oxide ore assayed only 0.1 percent copper and 40 feet of supergene sulfide ore averaged 1.793 percent. Other holes that show unusually good enrichment include hole 50 where 205 feet from a depth of 1,540 to 1,745 feet averaged 1.872 percent copper, and hole 58 where 345 feet from a depth of 1,455 to 1,800 feet averaged 1.572 percent copper. In comparison, about the richest zones of primary ore were found in hole 55 where 170 feet of ore from a depth of 1,455 to 1,625 feet averaged 1.018 percent copper, and a 60-foot section in hole 15 that averaged 1.44 percent copper.

A large percentage of the sulfide ore at San Manuel is primary, and evidence of supergene processes in this ore is absent or of negligible importance. In this respect San Manuel has similarities to Bingham and Ely where there was much enrichment but mining at depth has shown large amounts of primary ore.

The local variation in enrichment in the San Manuel deposit emphasizes the necessity for as nearly complete data as possible on all aspect of the geology, because conclusions drawn from the evidence in one part will be found inapplicable in another part. A proper understanding of results in even a single drill hole depends on recognition of the three types of primary mineralization that occur in and near the ore, and a recognition

of the variable effect of oxidation and secondary sulfide enrichment on the primary mineralized rock.

NATIVE COPPER

One of the most perplexing mineralogical problems at San Manuel is the explanation of the occurrence of native copper in the supergene zones. Generally it occurs in the lower part of the supergene sulfide zone although it may be absent in the upper and richer part. In only one hole was native copper abundant at the top of the supergene sulfide zone. In hole 89 a heavy concentrate of native copper was obtained by panning the sludge from 680 to 690 feet; lesser amounts of native copper occur in chalcocite below. This occurrence is a normal example of abundant oxygen robbing chalcocite of its sulfur to leave native copper. The native copper was in turn partly oxidized to cuprite. It is certain that part of the native copper lower down in the chalcocite zone was formed by replacement of chalcocite (pls. 3E, 6C). Hole 1 furnishes a good example. This hole started in the ore outcrop and passed through 520 feet of highly oxidized material averaging 0.614 percent copper. The supergene sulfide zone extended from 520 to 740 feet and averaged 1.158 percent copper. The hypogene zone contained moderate amounts of copper from 740 to 790 feet, but below 790 feet it graded into the pyritic footwall rock that averaged 0.291 percent copper from 790 to 990 feet. Near 680 feet—that is, in the lower part of the chalcocite zone—native copper occurs in considerable amounts. This was formed in part, if not completely, from chalcocite which is rimmed and veined by native copper. Chalcocite also occurs as remnants in some of the large fragments of native copper. It should be noted that there are 160 feet of supergene sulfide above the point where the native copper appears and that the native copper occurs throughout a thickness of 60 feet.

Although there is good evidence of the formation of some native copper from chalcocite, there is much copper which shows no remnants of chalcocite and therefore the possibility exists that some native copper was precipitated directly from supergene copper-bearing solutions.

The formation of native copper from chalcocite must result from oxidation of the sulfur in chalcocite, possibly by ferric sulfate, but it is difficult to explain how the ferric sulfate passed through the upper part of the chalcocite zone without reducing the chalcocite. If the occurrence were only in one or two holes, it might be accounted for by a lateral access of solutions, but the prevalence of native copper at depth indicates a chemical condition in the lower part of the chalcocite zone favoring reduction of chalcocite on a widespread but usually small scale. The presence of native copper far

down in the sulfide ore may well be connected with the abundant goethite found in both the supergene and hypogene copper sulfide zones. Both suggest the presence of oxygen at depth; but, as will be shown, the two do not occur together to any great extent.

OCCURRENCE OF IRON OXIDE BELOW THE OXIDE ZONE

Iron oxide is abundant in the oxide zone, as would be expected of a pyritic deposit. An unusual feature is the persistence of iron oxide (red goethite) in the chalcocite ore and also below important secondary sulfide. Study of assays of oxide copper² and of the mineralogy, shows that in many holes goethite, which formed by oxidation of pyrite, continues well below the place where copper sulfides have been extensively oxidized. This is true in holes A, H, V, 3, 6, 10, 44, 56, 79, and perhaps others. For example, hole 44 at 1,500 to 1,505 feet was estimated to have 30 percent iron oxide in the concentrate, but the assay shows only 0.04 percent copper as oxide, as compared with a total copper content of 0.56 percent. The concentrate of hole D at 1,330 to 1,335 feet contained 95 percent iron oxide, but the copper assay showed only 0.30 percent as oxide in a total 0.69 percent copper.

The relation of goethite to minerals other than pyrite is not clear, perhaps because they were formed at different times. However, in a polished section of concentrate from hole 6 at 1,045 feet, pyrite shows replacement by both chalcocite and goethite in the same grain, and there is a rude veining of goethite by chalcocite. This may in part explain some of the relations just described.

It is especially difficult to account for so much oxidation of pyrite below chalcocite which theoretically dissolves more readily than pyrite. Perhaps the explanation lies in the structural changes in the region. The evidence seems conclusive that the region was tilted to the northeast about 30° after the deposition of the late Tertiary conglomerate but previous to the deposi-

² The assay data available are of importance in the interpretation of the geology. For each 5-foot section of all drill holes a total copper assay is available, made under a standard procedure (Morenci method) applicable to low-grade copper ore. In addition, a determination of so-called oxide copper (copper in nonsulfide minerals) is made for all samples that assay an appreciable amount of total copper.

The procedure for determination of oxide copper, as supplied by the San Manuel Copper Corporation, is as follows:

1. Weigh 5 g. pulp into small vial (size 1 in. × 2½ in., with screw cover; capacity about 45 ml).
2. Add 30 ml saturated solution SO₂ (60 ml H₂SO₄ + 2500 ml H₂O, saturated with SO₂).
3. Cap bottles and agitate on shaker table 1 hr.
4. Remove and filter.
5. Wash 3 times with hot dilute H₂SO₄.
6. Wash 3 times with hot water.
7. Add 5 ml H₂SO₄ to filtrate, bring to boil. While boiling add 15 ml of 20% solution Na₂S₂O₅. Boil until solution is clear, or copper is precipitated.
8. Filter and wash 3 times with H₂O.
9. Ignite.
10. Transfer ignited precipitate to 250 ml beaker, add 10 ml H₂O and 5 ml HNO₃. Boil until all copper is in solution (about 5 min.).
11. Cool and neutralize with NH₄OH, add 10 ml acetic acid and boil.
12. Cool and determine volumetrically by iodide method.

tion of the alluvial slope deposits of the San Pedro Valley, which lie unconformably on the conglomerate. Furthermore, vertical sections of the deposit show a pronounced dip of the supergene sulfide zone to the south. The oxidation and enrichment evidently took place before the deposition of the conglomerate; so, it is difficult in the present stage of knowledge of the deposit to visualize the structural attitude of the ore body during enrichment. It is possible, even probable, that part of the deep oxidation took place at a different time and under different structural and climatic conditions from the supergene enrichment. It is also possible that some other unusual chemical condition resulted in an access of oxygen or of an oxidizing agent to the sulfide at depth. When the polished sections were studied, the possibility of an oxidation later than chalcocitization was considered, but because chalcocite was not oxidized to cuprite in most holes, except at the very top of the supergene sulfide zone, this explanation of the goethite deep beneath unoxidized chalcocite perhaps can be eliminated. It should be emphasized that much oxidation of chalcocite undoubtedly took place as erosion and accompanying oxidation migrated downward, but this has no obvious connection with the occurrence of goethite at depth. Perhaps oxidation of pyrite to goethite took place earlier than chalcocitization although there is little direct evidence of this. Oxidation below water level at depth along faults is a feature of several districts in Arizona, but the distribution of the iron oxide at San Manuel does not favor this explanation.

PARAGENESIS OF THE ORE MINERALS

The ore minerals include chalcopyrite, chalcocite, bornite, covellite, molybdenite, native copper, cuprite, chrysocolla, malachite, and azurite. Pyrite and goethite are abundant and important in the paragenesis of the ore.

The primary, or hypogene, ore consists mainly of disseminated pyrite and chalcopyrite, with very minor amounts of bornite. Chalcopyrite occurs as minute disseminations in the rock (pl. 2*E*) and as inclusions in pyrite grains (pl. 5*A*). In the low-grade, but highly pyritic, parts of the deposit most of the chalcopyrite occurs within the pyrite grains.

In the better grade hypogene ore a little bornite occurs with chalcopyrite, the two having common boundary relations. They are believed to be contemporaneous in origin. Rare, but of some significance, are crystallographic intergrowths of bornite and chalcopyrite, a replacement of chalcopyrite by bornite.

A small amount of molybdenite occurs in the primary ore. On the dump of shaft 2 it occurs mainly in quartz

veinlets; some molybdenite-bearing veins are earlier and others later than quartz-chalcopyrite veins.

Supergene sulfide enrichment has been active throughout large masses of the ore. The important change has been the chalcocitization of pyrite and chalcopyrite, but other complex mineralogical changes, more or less typical of supergene sulfide enrichment of copper ores, have accompanied the dominant process.

Chalcopyrite and pyrite occur in all conceivable stages of replacement by chalcocite (pl. 6*E*). Some chalcopyrite was largely replaced before the pyrite was extensively attacked. Locally, small remnants of chalcopyrite are abundant in chalcocite, where pyrite shows only slight attack, mainly as narrow rims of chalcocite surrounding the pyrite grains. Commonly, chalcocite which has replaced pyrite shows a concentric structure (pl. 6*D*).

Bornite is common but never abundant in the supergene ore. Rarely, chalcopyrite is replaced by bornite, leaving remnants similar to those commonly found in chalcocite (pl. 4*D*). The most common occurrence of bornite is as narrow zones or often merely a faint shadow around pyrite and chalcopyrite remnants in chalcocite (pl. 5*C*). It seems evident that bornite represents mainly a transitory stage in the replacement of iron-bearing sulfides by cuprous sulfide. Chalcocite adjacent to bornite often is a darker gray that fades out away from the bornite remnants.

Covellite is common but rarely abundant. The most striking occurrence is as a replacement of chalcopyrite, where it works out along the crystallographic planes (pl. 4*C*). Commonly, covellite forms only a narrow zone between chalcopyrite and chalcocite and, exceptionally, a sequence from chalcopyrite through bornite and covellite to chalcocite is displayed (pl. 5*C*). Covellite commonly occurs along the margins of chalcocite, working in as small tufted aggregates, and locally the chalcocite is extensively replaced throughout by covellite. Covellite even more than chalcocite shows a preference for chalcopyrite as a host and rarely, if ever, replaces pyrite directly; but pyrite remnants may remain in covellite that has replaced chalcopyrite or chalcocite. In a few grains of chalcocite the covellite is so evenly distributed that an origin by exsolution is suggested, as shown by Bateman and Lasky (1932, pp. 52-86) for the Kennecott ore.

Native copper is a common constituent of parts of the supergene sulfide zone in about one-third of the drill holes, as has been remarked in some detail in the description of that zone.

Oxidation has resulted in extensive changes in the mineralogy of the ore. Chrysocolla is the principal copper mineral developed by alteration of chalcocite,

and perhaps of other copper minerals, and probably by copper solutions precipitating the silicate on contact with silica in solutions. Chrysocolla occurs to a marked extent as coatings along fractures rather than as disseminations like the copper sulfide minerals.

Where oxidizing solutions had free access to chalcocite ore, alteration to cuprite may be readily observed (pls. 5*D*, *E*). This does not seem to have been quantitatively important except locally, unless the cuprite so formed was later altered to chrysocolla. Various stages of oxidation of chalcocite to cuprite were observed. In some grains, rim texture in varying degrees of development is present, whereas in other grains a minute network of cuprite veinlets cuts the chalcocite (pl. 4*A*).

GENESIS OF THE ORE

Most of the factors involved in the formation of the San Manuel copper deposit have been discussed in appropriate sections of this report. A brief summary of the processes will serve to clarify the present ideas. It is clear that the principal rocks of the area, quartz monzonite, monzonite porphyry, and diabase, had been emplaced before the primary ore was introduced. It is equally clear that the later rocks, mainly the Gila (?) conglomerate and the intruded rhyolitic rocks had not been formed. The deposit, as it now exists, represents a combination of hypogene and supergene processes.

The granite quartz monzonite (Oracle granite) is known to be particularly extensive in the surrounding area, and both monzonite porphyry and diabase have been observed in considerable amounts in the area mapped. None of these rock exposures, aside from the limited area of the San Manuel deposit, is known to contain important amounts of copper, and most of these rocks are entirely barren. This indicates that although these rocks are important hosts, none of them is known to account genetically for the ore to which they play host. Because of the occurrence of copper at many places in monzonite porphyry, it seems logical to infer that the copper at San Manuel is related to the episode of intrusion that emplaced the monzonite porphyry and was followed by intrusion of diabase dikes, with mineralizing solutions coming after both intrusions.

The close relation of the hypogene sulfide minerals, pyrite and chalcopyrite, to the hydrothermal alteration of the earlier rocks leaves no reasonable doubt that the introduction of copper was but an incident in the complicated processes that resulted from the invasion of the area by hydrothermal solutions that varied in composition at different times, probably corresponding to different stages in their development.

The difference between the area centering around the San Manuel ore body and adjacent areas is this intense hydrothermal alteration of the rocks older than the rhyolite and the Gila (?) conglomerate. There is some alteration of the rocks over a very wide area, but it is mainly of the marginal biotite type or is intense only along fissures.

In the San Manuel deposit the solutions at one stage introduced some potassium and in addition caused that already present to crystallize as sericite, and this particular stage in the evolution of the solutions seems to have been favorable to the transportation of copper and its deposition, principally as chalcopyrite, with sericite and associated minerals.

The source of the hydrothermal solutions is uncertain. Judging by most of the other "porphyry" or disseminated copper deposits, one would say that they gained their load of mineralizers and metals at depth from the place of origin of the intruded monzonite porphyry. Diabase that cuts the porphyry is also mineralized. The problem of diabase dikes was considered by Ransome (1919, p. 168) for the Globe-Miami-Ray region. In parts of this region there was no association between ore and diabase, and Ransome concluded that the diabase had no essential relation to the deposition of the ore. This applies to the San Manuel area as well, because there are many diabase dikes in the area near the ore bodies and some extensive ones a few miles to the northwest, but none shows evidence of active mineralizing solutions except at San Manuel.

These facts suggest two possibilities that together may account for the copper deposit and adjacent areas of intense alteration. First, there must have been a source of hydrothermal solutions in the area. The increase in amount and depth of monzonite porphyry eastward suggests that a stock may exist still farther east, and, by analogy with other districts, this might be a possible source.

In addition to the source, it was also necessary to have a large block of ground that was fractured thoroughly enough to permit the altering and metallizing solutions completely to permeate the rocks. The completeness of the alteration and metallization of the rock in the ore zone, as well as in the pyritic and alunitic zones, indicates a complete shattering of the rocks, as is characteristic of great disseminated copper deposits. Present data do not reveal the cause or control of this shattering. The area has been much faulted, but the faults that can be mapped are all postore, because they offset the beds of Gila (?) conglomerate. The presence in the rocks below the conglomerate of many shear zones that cannot be correlated with known faults is an indication of earlier major displacements that may be responsible for the widespread shattering.

The conditions at San Manuel seem effectively to dispose of the suggestion that shattering of the rock in the "porphyry copper" deposits was a result of cooling of the intruded porphyry. The grade of the ore is remarkably uniform in pre-Cambrian quartz monzonite, in much younger (Mesozoic or Tertiary) monzonite porphyry, and in diabase. A tectonic origin seems necessary to account for equal shattering of three distinct rocks of different age.

Following the deposition of the primary copper deposit, there was evidently a long period of erosion that eventually exposed the deposit at the surface where meteoric solutions had an opportunity to permeate the part near the surface.

The fact that the hanging wall is a lean zone of moderate alteration containing little pyrite evidently had an important bearing on the progress of oxidation and supergene enrichment. Enrichment is negligible where a great thickness of tight hanging-wall rocks exists. There seems to have been a lack of sufficient sulfuric acid in part of the deposit to dissolve the copper and carry it downward as copper sulfate; therefore, enrichment is weak and much copper remains in the oxide zone as chrysocolla. Where pyrite was abundant, as at the east end of the San Manuel ore body, leaching of the ore zone is extensive and high-grade chalcocite ore exists below.

The age of the copper deposit is not known. As indicated by the data presented thus far, the copper mineralization took place after the emplacement of the quartz monzonite, monzonite porphyry, and diabase, and it is earlier than the emplacement of rhyolite and Gila(?) conglomerate. Inasmuch as the age of the porphyry and diabase are problematical, not much remains to serve as definite markers of time, but by analogy it seems highly probable that the ore at San Manuel is of the same age as that at Ray, Miami, and Globe.

Ransome (1919, p. 169) had the same difficulty in fixing a date for those deposits. He says, "It appears reasonable to regard the intrusion of the granitic porphyries as an early Tertiary event, but it must be admitted that this is little more than conjecture."

The series of sedimentary rocks of various ages in this part of Arizona are so fragmentary that more precise dating of events may remain impossible.

RELATION TO DEPOSITS AT THE ST. ANTHONY MINE

Although at some points the San Manuel and St. Anthony mine deposits are less than a mile apart, there is a sharp contrast between them, and it seems a reasonable inference that they have different origins and evidently were formed at different times.

Some of the contrasts are shown in the following table. The characteristics of the St. Anthony deposit are taken from reports by N. P. Peterson (1938a, p. 30-33) and by S. C. Creasey (1950, pp. 63-84).

The San Manuel deposit, like other disseminated copper deposits, may be classified as mesothermal. On the basis of the combination of structure and mineralogical associations, Peterson suggests that the deposits of the St. Anthony mine may be classified as belonging to a high-temperature, shallow type of mineralization.

Taking into account the close relation of the San Manuel deposit to the monzonite porphyry, one might venture the suggestion that there is a genetic relation, or that the copper is related to the intrusion of the diabase dikes. The St. Anthony deposits are closely associated with later rhyolite and associated intrusive breccia. It is a reasonable inference that at St. Anthony the metalizing solutions were associated, at least remotely, with the episode of igneous activity represented mainly by the rhyolite which is postore in the San Manuel deposit.

Comparison of San Manuel and St. Anthony deposits

| <i>San Manuel</i> | <i>St. Anthony</i> |
|--|---|
| Disseminated ore. | Ore in fissures or brecciated zones and faults. Both open-space deposition and replacement. |
| Monzonite porphyry and quartz monzonite principal host rocks. | Rhyolite intrusive breccia, and quartz monzonite wall rocks in ore zone. |
| Ore is prerhyolite. | Ore is postrhyolite. |
| Known faults, mainly, if not entirely, postore. | Faults mainly preore except those of small displacement. Ore controlled by faults. |
| Copper with very minor amounts of other metals. Lead, zinc, vanadium practically absent. Small amounts of molybdenum. Intense, widespread hydrothermal alteration. | Principal metals: gold, zinc, lead, molybdenum, vanadium. |
| Enormous amounts of pyrite, chalcopyrite important. | Wall rocks hydrothermally altered for only a few feet. |
| Silicification unimportant. Vein quartz of very minor importance. | Pyrite relatively unimportant, chalcopyrite of minor importance. |
| Widespread sericitization. | Considerable silicification. Deposition of vein quartz, much of which replaced fault breccia and gouge. |
| Alunite an important hydrothermal mineral in adjacent zones. | Sericite unimportant. |
| Calcite unimportant. | Alunite not recognized. |
| Specular hematite not recognized. | Calcite abundant in veins. Vein calcite as much as 2 feet wide. |
| Adularia rare. | Specular hematite abundant on lower levels, particularly at the northern veins of the mine. |
| Fluorite not recognized; barite very rare. | Adularia fairly common. |
| | Microscopic fluorite fairly abundant and widely distributed. |
| | Barite common. |

POSSIBILITIES IN ADJACENT AREAS

Intimate knowledge of the San Manuel deposit gathered from field and laboratory studies during most of the exploration should be a valuable basis for judging the possibilities of adjacent areas, and areas farther removed. Sporadic independent exploration by drilling at several places within a few miles of San Manuel has been going on since the possibilities of the known deposit were recognized. Most of this work has been done with little regard for the fundamental conditions that determined the copper content at San Manuel; and, accordingly, considerable money and effort might have been saved by more careful geologic work preceding actual drilling.

The characteristic geologic feature of the San Manuel deposit and its immediate vicinity is the intense alteration of the host rocks. This alteration is not only widespread horizontally but extends vertically from the surface exposures to the greatest depth reached in the drilling (2,755 feet). The highly altered ore zone extends from the surface to great depths at angles of 50° to 65°. Thus far, hydrothermal alteration of the rocks is the most valuable guide in the search for other metallized areas. Conversely, there is no basis at present to justify an expectation of ore below surface rocks that show little or no hydrothermal alteration, except in well-defined fissures as in the St. Anthony mine.

In the absence of a knowledge of the major structural control of the San Manuel deposit, major structural trends in the district cannot be predicted. It should be understood that the known faults affecting the San Manuel are postore and therefore are not guides to the deposition of ore, although they have an important effect on the nature of any ore-bearing ground that may be found.

The general trend of the ore body is in a direction N. 60° E., with a south dip for the western part, which has a well-defined tabular shape. This suggests a structural control for the copper-bearing solutions having that general direction of flow. Present evidence suggests a more complex control for the solutions that deposited the extensive pyritic zone, and a great amount of additional exploratory work will be required to outline the complete boundary of that zone.

Exploration of the area east of the San Manuel Copper Corporation and Houghton Group ground is greatly complicated by the existence of the San Pedro Valley. The maximum thickness of the alluvial fill and interbedded volcanic rocks in the valley is not known but is believed to be very great. It is reported that a drill hole about a mile northeast of Tiger penetrated 2,020 feet of alluvial gravels and conglomerate without passing into older rocks.

Others have noted that the fill in the San Pedro trough is very thick; for example, Davis and Brooks (1930, p. 109) state that at Benson a well was drilled 1,505 feet in sand and gravel without passing out of this material. Because of the thickness of the gravel and conglomerate in the San Pedro Valley, exploration in it should be undertaken only with a full appreciation of the difficulties involved.

North of Tiger is a large area of volcanic rocks, and, locally, small veins carrying copper minerals occur in these rocks. Present knowledge indicates that these minor deposits are younger than the San Manuel deposit, and, as they occur in radically different rocks, any deposits that may exist will probably be found to follow a very different pattern. This does not mean that commercial deposits are not to be found, but that prospecting for them should be based on the geology at the site.

The Pearl mine, about 3½ miles northwest of Tiger, has shipped a considerable tonnage of oxide and sulfide copper ore. Records are not available, but the amount is estimated at 50,000 to 60,000 tons. Comparison of the dump and the stopes visible through caving at the surface tends to verify this estimate. The mine followed a well-defined fissure in granite, and a conspicuous contrast to the San Manuel deposit is the virtual absence of hydrothermal alteration in the wall rock. Other exploration pits in the vicinity show a similar occurrence.

About 2 miles southwest of San Manuel an area of porphyry and quartz monzonite extends along both sides of State Highway 77 (fig. 3). East of the highway there are shear zones in the porphyry where sericite is abundant in a narrow belt, but old test pits reveal no evidence of metallic minerals.

The best opportunities for prospecting appear to be afforded by areas where the cover of conglomerate and gravels over the igneous rocks is not too thick for the latter to be tested by relatively shallow drill holes, with the possibility of penetrating hydrothermally altered areas that might be explored for evidences of the various types of alteration.

RESERVES

Estimates of reserves of the San Manuel deposit have been published by the Magma Copper Company and its subsidiary, San Manuel Copper Corporation, at various times during the exploration. The U. S. Bureau of Mines gave complete data at the time its drilling program was completed (Chapman, 1947).

The Geological Survey cooperated in preparing the Bureau of Mines' figures, and all data fundamental to the calculation of reserves were freely provided by the

company throughout the later work. Separate calculations were considered unnecessary.

Calculations of reserves were made by the company engineers as exploration progressed, and these were checked by the consulting engineer, Arno S. Winther. The tonnages are based on a "cut-off percentage of 0.5 percent copper." The general methods used were discussed by Steele and Rubly (1947).

The following figures are taken from a prospectus issued by the company February 15, 1949:

| Sulfide ore | Tons | Total copper (percent) | Oxide copper (percent) |
|------------------------|---------------|------------------------|------------------------|
| North ore body----- | 178, 762, 616 | 0. 784 | 0. 036 |
| Southeast ore body---- | 160, 284, 920 | . 795 | . 025 |
| Total sulfide ore----- | 339, 284, 920 | 0. 789 | 0. 031 |
| Oxidized ore | | | |
| Copper 0.5+ percent-- | 123, 499, 580 | 0. 767 | ----- |
| Total ore----- | 462, 784, 500 | ----- | ----- |

Higher grade sulfide ore has been calculated as 150,416,100 tons; total copper 0.898 percent.

Higher grade oxidized ore (0.7+ percent copper) 73,165,957 tons; total copper 0.866 percent.

A striking feature of the deposit is the very large amount of mineralized rock of low grade, that is, below 0.5 percent copper content.

For example, a block of ground was computed from coordinate 200 E. to coordinate 2,200 W. where the better grade rock has a fairly regular tabular shape and a thick hanging-wall zone of low-grade ore in holes near

its southern limit. This block was estimated to contain 146,527,000 tons of ore, averaging about 0.69 percent copper and containing 1,012,800 tons of copper. This is a part of the reserves noted above. The same block was estimated to contain, in addition, 146,288,000 tons of rock that varied between 0.2 and 0.5 percent copper and averaged 0.3 percent. The copper content as estimated is 437,548 tons. It should not be assumed that the ratio of low-grade rock to ore applies to the deposit as a whole, because there is probably proportionately less low grade in the eastern part of the deposit where the greatest reserves of sulfide ore exist.

The ore is calculated on the basis of 12.5 cubic feet of rock to the ton. This is a conventional figure for disseminated copper ore, but the figure at San Manuel was validated by careful determinations of specific gravity of mineralized rock from hole 59 which was drilled with a rotary drill using a Hughes bit, and the core was recovered for this purpose. (See table 6.)

The average copper content of the oxidized ore and of the sulfide ore do not differ much and there is a very small difference between the specific gravity of the monzonite porphyry and the quartz monzonite ore.

The ore body extends eastward into ground explored by the Houghton Group, but no estimate of reserves has been published for this extension.

AEROMAGNETIC DATA

The area of the Mammoth 7½-minute quadrangle was surveyed with the airborne magnetometer; traverses were about one-fourth mile apart. The vicinity of the

TABLE 6.—Specific gravity tests of rock specimens from rotary-drill hole 59

[Data by courtesy of San Manuel Copper Corporation]

| Sample | Depth (feet) | Rock | Specific gravity | Cubic feet per ton |
|--------|--------------|--|------------------|--------------------|
| 1 | 1, 000 | Monzonite porphyry, dark, fine-grained, hard, well-consolidated----- | 2. 618 | 12. 24 |
| 2 | 1, 050 | Monzonite porphyry, more altered and oxidized and with more clay minerals than no. 1, some hematite. | 2. 577 | 12. 43 |
| 3 | 1, 070 | Monzonite porphyry, top of oxide ore, some chrysocolla, moderate alteration----- | 2. 516 | 12. 73 |
| 4 | 1, 080 | Monzonite porphyry, badly broken and crumbly, well-oxidized, coarse porphyry----- | 2. 587 | 12. 40 |
| 5 | 1, 085 | Quartz monzonite, well-oxidized and sericitized, chrysocolla, fault gouge and clay in seams--- | 2. 516 | 12. 73 |
| 6 | 1, 120 | Quartz monzonite, similar to no. 5, crumbly----- | 2. 548 | 12. 57 |
| 7 | 1, 145 | Quartz monzonite, oxidized, hard, well-consolidated----- | 2. 552 | 12. 55 |
| 8 | 1, 175 | Quartz monzonite, top of mixed oxidized and sulfide ore, still well-oxidized, some chalcocite, chalcopyrite, and hematite. | 2. 567 | 12. 51 |
| 9 | 1, 180 | Quartz monzonite, similar to no. 8, fresher----- | 2. 567 | 12. 50 |
| 10 | 1, 180+ | Rhyolite----- | 2. 541 | 12. 61 |
| 11 | 1, 280 | Quartz monzonite, leached, well-altered----- | 2. 494 | 12. 85 |
| 12 | 1, 305 | Quartz monzonite, mixed oxidized and sulfide ore, disseminated sulfide ore----- | 2. 570 | 12. 47 |
| 13 | 1, 430 | Monzonite porphyry, mixed oxidized and sulfide ore----- | 2. 587 | 12. 42 |
| 14 | 1, 482 | Monzonite porphyry, probably top of sulfide zone, disseminated pyrite and chalcocite----- | 2. 620 | 12. 23 |
| 15 | 1, 540 | Monzonite porphyry, fresh looking, much biotite, sulfide ore----- | 2. 572 | 12. 46 |
| 16 | 1, 590 | Monzonite porphyry, well-mineralized sulfide ore, chalcopyrite and pyrite moderately abundant. | 2. 711 | 11. 82 |
| 17 | 1, 600 | Quartz monzonite, well mineralized sulfide ore----- | 2. 645 | 12. 11 |
| 18 | 1, 600+ | Quartz monzonite, similar to no. 17----- | 2. 644 | 12. 12 |
| 19 | 1, 605 | Quartz monzonite, similar to no. 17----- | 2. 687 | 11. 96 |
| 19 | 1, 605 | Quartz monzonite (check test on no. 19)----- | 2. 665 | 12. 02 |

For comparison, specific gravity tests for samples from three other areas are given:

Three specific gravity tests by T. S. Lovering (1948, p. 5)

| Rock | Location and zone | Density (bulk) | Density (powder) |
|--------------------|---------------------------------|----------------|------------------|
| Quartz monzonite | Red Hill, pyrite-hydromica zone | 2.454 | 2.702 |
| Monzonite porphyry | Hole 73, marginal zone | 2.475 | 2.598 |
| Monzonite porphyry | Hole 15, ore zone | 2.544 | 2.648 |

San Manuel deposit is characterized by a zone of relatively weak magnetic intensity slightly more than 2 miles long. The zone is elongated in a direction N. 65° E., or about parallel to the strike of the San Manuel ore body, and an extension has a projection northward through Tiger. The San Manuel ore body, as presently known, lies at the junction of the projection and the main area.

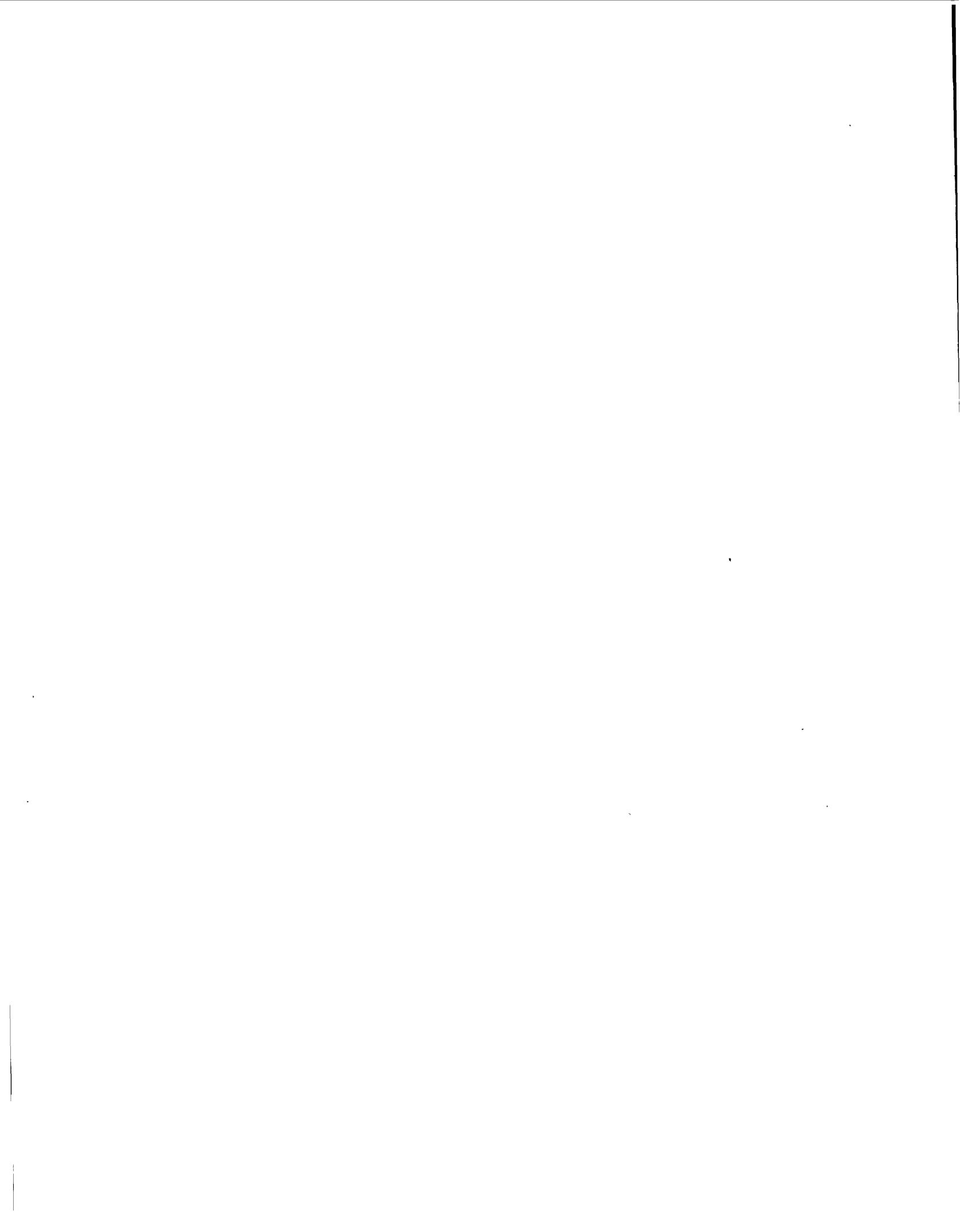
It is probable that the area of low magnetic intensity is, in part, a result of the destruction of magnetite by hydrothermal alteration. Whether this may be applied to the entire area of low intensity is uncertain, but interesting possibilities may be indicated.

A circular area of high magnetic intensity exists about 4,500 feet west of BM 3,579 on the Mammoth quadrangle. Unfortunately, alluvial wash from a hill to the south covers the bedrock in that area and no reason for the anomaly could be discovered.

Northwest of Tiger an area of basic volcanic rocks is bounded on the west side by a fault (fig. 3). The approximate position of this fault is shown on the magnetic map by a crowding of roughly north-south isomagnetic lines.

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