1965

Petrology and mineralogy of the "Old Workings Area," El Salvador, Chile

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PETROLOGY AND MINERALOGY OF THE "OLD WORKINGS AREA," EL SALVADOR, CHILE

BY

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THESIS

submitted to the faculty of

THE UNIVERSITY OF MISSOURI AT ROLLA

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE IN GEOLOGY

Rolla, Missouri

1965

Approved by

______________ (advisor) ______________

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ABSTRACT

The "Old Workings Area," so called for its early mining by the Incas, is located 4½ miles northeast of the El Salvador Porphyry copper deposit, the third largest copper producer in Chile. The area mapped in this study is shown to consist of rhyolite pebble conglomerate, two volcanic flows, andesite and rhyolite porphyry, and two intrusions, quartz porphyry and tourmaline-bearing breccia.

Petrographic study of surface and drill core rock samples confirms the field nomenclature used for the five rock types. All of the rock types are altered, but the quartz porphyry and andesite are the most intensely altered. Both hydrothermal and weathering actions have contributed to the alteration.

Ore microscopic investigations of selected polished surfaces showed that pyrite, chalcopyrite, and molybdenite are the primary sulphides in the "Old Workings Area." The secondary copper minerals, chalcocite and covellite, replace the primary sulphide minerals. At the surface the copper sulphides are oxidized to brochanthite, chrysocolla, and antlerite. Hematite, hausmannite, and braunite locally are present as fracture coatings.

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I. INTRODUCTION

A. Purpose of Investigation

The purpose of this investigation was to map and study an area three miles northeast of El Salvador, Chile. Geologic mapping, determination of the relationships between the rock units, and the collection of representative specimens were the main activities in the field. The determination of the lithologic types, primary sulphide mineralogy and secondary supergene mineralogy constituted the principal emphasis in the laboratory portion of this investigation.

B. Location and Size of Area

The area mapped for this investigation lies in Atacama Desert, in Atacama Province, about seventy-five miles east of the coastal town of Chanaral and twenty miles north of Potrerillos (see figure 1). It is about four and one half miles northeast of Indio Muerto Peak, beneath which the El Salvador deposit is mined.

The mapped area is nearly rectangular in shape, with a length of about 1250 meters and a width of about 750 meters. In the central portion of the area, copper was mined possibly as early as pre-Inca times. These workings are locally referred to as the "Old Workings," and for the purpose of this study, the entire mapped area will be referred to as the "Old Workings Area."

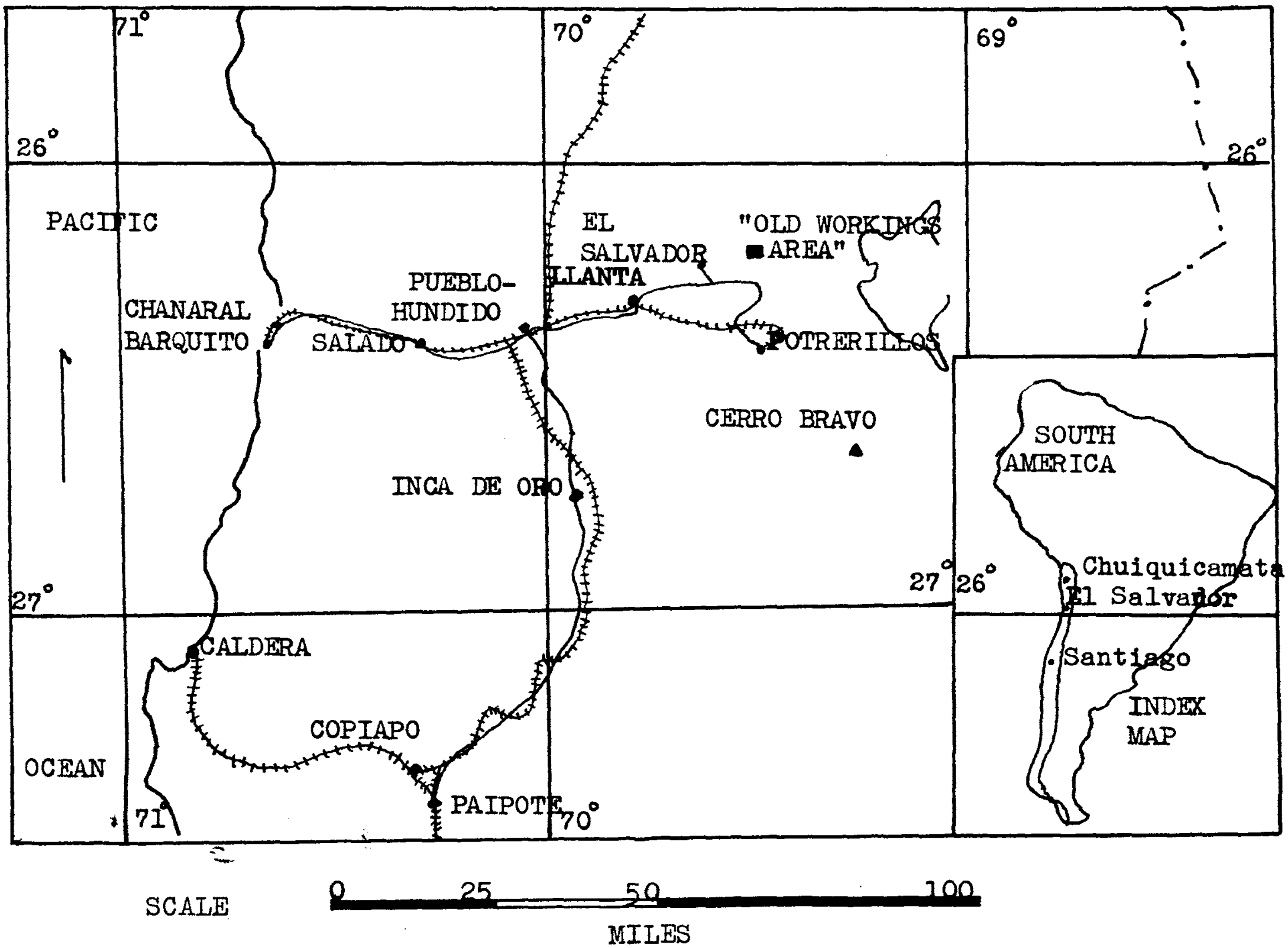


FIG. 1. GEOGRAPHIC LOCATION OF "OLD WORKINGS AREA"

C. Topography

The area is characterized by a rather mature topography, with rounded forms. The entire region, as seen from the air, appears to be a well developed normal stream relief partly buried under alluvial fans. Many isolated ridges and small hillocks, partly covered by debris due to mechanical weathering of the rock, emerge from beneath the alluvium.

The maximum elevation is 2805 meters and the minimum elevation is 2615 meters above sea level. The maximum relief is 190 meters, but the average relief is 25 meters between the gravel washes and the ridges.

Two gravel washes form the boundaries of the area mapped; one forms the northern and eastern borders and the other forms the western border. The southern border is marked by the highest hill in the area, which has an elevation of 2805 meters above sea level.

Four ridges extend from the highest point, the highest point being on a ridge extending northwest into the area. The crests of these ridges slope to the northwest. The two gravel covered washes converge at the end of the westernmost ridge.

The ridges generally are controlled by the quartz porphyry while the valleys are underlain by andesite. Three tourmaline volcanic breccia pipes form ridges. The rhyolite and the conglomerate are exposed along the western flank of the northwestern ridge just east of the western border. The conglomerate also outcrops in the extreme northern part of the area.

D. Climate and Vegetation

The arid climate of the Old Workings Area is characterized by an average annual rainfall of four tenths of an inch. This meager rainfall occurs principally during the winter months and the water supplies for the remainder of the year are dependent on this seasonal precipitation. It quickly permeates the surface gravels and reappears as springs where the water encounters impermeable shales at lower elevations. Rainfall reaching the Ola River provides most of the water for the El Salvador mine and mill and the Potrerillos smelter operations. A pipeline from the dam on the Ola River, at an elevation of 11,650 feet above sea level, transports that water down to El Salvador and Potrerillos at an elevation of 9,500 feet above sea level.

The Old Workings Area lies approximately 200 miles south of the Tropic of Capricorn. The temperature ranges from just below freezing to moderate temperatures during the winter months, May to September, and from moderate temperatures into the ninties during the summer months. Field work can be undertaken throughout the year.

The prevailing winds usually are from the west. The area is characterized by high winds, gaining velocities as high as sixty miles per hour. Winds commonly reach an average of fifteen to twenty miles per hour.

As a result of the prevailing winds, cumulus clouds occasionally reach as far inland as El Salvador and frequently bring precipitation with them. The clouds form at the edge of the Andes Mountain Range and drop most of the precipitation as they rise up to pass over the higher peaks.

Sparse vegetation is characteristic of the area. Sagebrush, greasewood, and many varieties of cactus are the only plants in the desert. Trees and plants foreign to the area have been planted about the homes in the towns of El Salvador and Potrerillos.

E. Culture

The Atacama Province is sparsely populated. The main centers of population are the mining camps of El Salvador, Potrerillos, Llanta, and Barquito, but a few people live in small villages along the only major road which connects Potrerillos to the coastal town of Chanaral. This major road is paved only from El Salvador to Llanta. The streets in El Salvador, Potrerillos and Llanta also are paved. All the other roads in the area are dirt, except those in the coastal towns.

Bus service is available daily along the partly paved road from Potrerillos to the coast, where bus connections can be made to other points along the coast. A chartered bus line serves to transport the workers to the plant and El Salvador mine.

There are two railroads in the area, one owned by the Andes Mining Company and the other owned by the Chilean Government. The railroad owned by the mining company connects Potrerillos to Pueblo Hundido and is operated for the purpose of freight only. The Chilean National Railway operates service from the Pueblo Hundido to all other parts of Chile. The mining company has an agreement with the Chilean Government to use its tracks to haul copper to the company coastal town of Barquito.

In the early days, cars were mounted on train wheels and converted to track cars, the steering wheel becoming the brake. It was a dusty days trip from Barquito to Potrerillos in those days. The track cars are still used, however, since the roads are good, but not as frequently.

The area is served by a commercial airline, the Ladeco Airline, which connects Potrerillos and El Salvador with Santiago, Antofagasta, and Calama. A small paved airport at El Salvador serves two privately owned aircraft and the Ladeco DC-3's when weather conditions do not permit landings at Potrerillos. By air, Antofagasta is only one and a half hours, Calama only two and one half hours and Santiago, the capital of Chile, is only two and a half hours from Potrerillos.

The area bears witness to the early presence of the Inca's, who inhabited much of Chile in the fifteenth, sixteenth and seventeenth centuries. An old Inca trail crosses the flat pampa to the south-west of the El Salvador mill.

The well worn trail continues from the coast into the mountains. The trail is still easily recognized due to the fact that it is about twelve inches deep. An old burial ground, located about one mile north-east of El Salvador, has been the source of many artifacts. Many of the old pits and tunnels of the old workings are believed to have been worked by the Inca's. The diggings and tunnels follow the rich veins of chrysocola. North-east of the old workings, foundation remnants, slag, and piles of low grade ore have been referred to the activities of the Inca's.

F. Field and Laboratory Procedure

The geodogy of "The Old Workings Area" was mapped by triangulation and tape and compass and plotted on a base topographic map having a scale of 1:5000. Two claim markers in the area, HR-1 and PP, previously surveyed, served as triangulation points. Seven old drill holes, which were flagged to make them more easily identifiable at a distance, were used as subsidiary base points. The locations of these drill holes were determined by triangulation and plotted by tape and compass traverses to the nearest claim marker.

After completing the geologic map, surface samples were collected from fifty-four localities, selected on the basis of geologic mapping.

Drill cores from six diamond drill holes were examined and of these, drill hole number 4 (251.1 meters deep), drill hole number 6 (385.47 meters deep), and drill hole number 9 (376.67 meters deep), were selected for sampling. Tourmaline-bearing breccia, quartz porphyry, and andesite were sampled from diamond drill hole number 4. The richest copper mineralization in the area was intersected and sampled in diamond drill hole number 6. Tourmaline-bearing breccia was sampled from diamond drill hole number 9. All three drill holes sampled exhibited a marked increase in pyrite content downward.

Sixty thin sections of drill core and surface specimens were prepared by the writer using an Ingram Ward thin section cut-off saw and an thin section grinder. Twenty polished sections were mounted in leucite, bakelite, and plastic. The writer found one quarter micron diamond, alumina, and finally magnesia produced the best polish.

The sections were examined with petrographic and ore microscopes to determine the texture and mineralogy of each specimen. Plagioclase composition was determined by the universal stage Rittman Zone Method Plagioclase Determination. This method depends upon a precise measurement of angle of extinction of plagioclase twinning lamella. The measured angles placed on curves given by Emmons (1943) determine the plagioclase composition.

Orthoclase present in thin sections was determined by staining. The cover slide was removed along with the excess balsam and cadex. Hydrofluoric acid was spread on the section with a brush and allowed to remain on the slide for a period of fifteen to twenty seconds. The slide was then soaked in sodium cobalt-nitrite for twenty to thirty minutes. The slide is then washed in water and if orthoclase is present it is stained yellow. The staining must be performed with rubber gloves under a hood, for the hydrofluoric fumes and liquid are extremely dangerous.

All grain size measurements were calculated by averaging the width and length of each grain or crystal except where noted otherwise.

G. Acknowledgements

The writer wishes to thank Dr. Richard D. Hagni for directing the thesis and for his suggestions, careful assistance and friendly guidance. The writer also is indebted to the people employed at Andes Copper Mining Company, El Salvador, Chile and Potrerillos, Chile, especially to Dr. Frank Trask, chief geologist Andes Copper Mining Company, for suggesting the thesis and for field guidance.

Gratitude is expressed to Mr. and Mrs. W. J. Bennett and other residents of Potrerillos and El Salvador mining camps for their warm hospitality.

II. GENERAL GEOLOGIC SETTING

A. Previous Investigations

Previous investigations in Chile are mainly in Spanish and German. Three papers in English pertinent to this thesis and one dealing with the El Salvador area are discussed below.

Cristi (1959) described the stratigraphy and general geology in the chapter on Chile in the Geological Society of America Memoir dealing with all of South America. The purpose of this memoir is to supplement the geologic map of South America. Cristi subdivides the northern part of Chile, the El Norte Grande, from the Peruvian border to Latitude 27 south, into three physiographic units. These units are: the coast range, the Pampa del Tamaragugal, and the Andes.

Harrington (1961) discussed the stratigraphy of the Antofagasta and Atacama Provinces in northern Chile, north of Latitude 26 south. While Harrington discussed the igneous and metamorphic rocks, he was principally interested in the sedimentary rocks and the oil content. He emphasized the brevity of geological study and the fact that much of the geology, except for stratigraphy of some areas, is imperfectly known.

Kents (1963) studied numerous breccia pipes throughout South America and attributed their formation to hydrothermal activity.

Swayne and Trask (1960) are the only authors to publish in English on the El Salvador area. They gave a detailed account of the stratigraphy, structure, mineralogy and alteration in the area immediately surrounding the El Salvador mine. The El Salvador mine, which is operated by the Andes Copper Mining Company, a wholly owned subsiderary of the Andaconda Company, is a porphyry-type deposit. All of the ore comes from the enriched layer which is principally chalcocite, but also has chalcopyrite, cuprite, and native copper. The ore minerals are disseminated mainly in fine-grained granodiorite and granodiorite porphyry. The igneous body intrudes andesite and rhyolite.

The following sections on petrology and structure are based upon the references cited above.

B. Petrology and Age Relations

The consolidated rock types exposed in the El Salvador area consist of older extrusives and younger intrusives. The extrusives are subdivided into three cycles. The oldest of these began in the middle Triassic and lasted into the upper Triassic. The rock types of this cycle are keratophyric varieties of slightly oversaturated soda trachytes, but rhyolite and andesite are intercalated with the keratophyres, especially near the top of the sequence.

The second cycle of extrusives began during the late Jurassic. They are mainly andesites, which are called pophyrites in Chile, following the German nomenclature for pre-Tertiary andesites. Much basalt and some rhyolite is associated with these andesites.

The vulcanites of the third cycle are interbedded with sandstone of both continental and marine origin. Their age is hard to determine for they form sills and laccoliths as well as flows.

In the Chanaral-Taltal area, ninty miles to the west of El Salvador, along the west coast of Chile, thick keratophyres and andesite flows and tuffs are intercalated with grayish green and dark gray shales. These rocks are younger than the extrusives of the three cycles discussed above, but are absent from the El Salvador area.

The younger intrusives, which are exposed throughout the El Salvador area, consist of granodiorite, granodiorite porphyry, diorite porphyry and quartz porphyry. These porphyries are believed to be Cretaceous.

The breccia pipes discussed by Kents (1963) are younger than the porphyry group.

C. Structure

The tectonic structure of the El Salvador and "Old Workings Area," is complex regionally, but simple locally. Jurassic sediments and Tertiary andesites form an imbricate structure with westward dipping reverse faults. Since the Jurassic beds also dip to the west, the reverse faults are not always easily distinguished. The Jurassic sediments were warped into broad regional folds prior to the reverse faulting.

Gentle monoclinal folds display a broad dome structure. While Jurassic sediments are exposed on the western and northwestern limb of the dome, the eastern limb is concealed by a dry salt lake called the Salar de Pedernales. The core of the dome is formed by pre-Jurassic granite, and its axis strikes north-northeast. The dome appears to be cut longitudinally by a vertical fault which marks the eastern limit of the granite. This fault brings the granite into contact with Tertiary andesites to the east.

The Pedernales Salar on the east limb is famous for its oil seeps which were drilled for water. The seeps are arranged in a straight line across the salar or salt lake. The artificial wells have been enlarged many years ago in an attempt to increase the oil seepage.

The "Old Workings Area" lies in the Principal Cordillera, which consists of more or less parallel ridges, separated by wide longitudinal valleys filled with wash from the surrounding mountains. The westernmost ridge rises steeply above the coast to reach an average elevation of 4200 feet above sea level. The coast is characterized by longitudinal faults of great vertical displacement. These faults are responsible for the subvertical cliffs along the coast and correspond to the Coast Range of Cristi (1959). That these faults are still active is indicated by the frequency of the earthquakes in their vicinity.

The longitudinal valleys cut through the parallel ridges along the coast and provide an easy access to the pampa region on which El Salvador is located. Just east of the El Salvador, the main chain of the Andes rise to form the great volcanic ridge.

The local structure of El Salvador is characterized by volcanic flows which subsequently were arched, folded and faulted. Overthrusting of these deformed rocks took place during the main Andian uplift in Cenozoic time.

Fracture zones in the El Salvador area have influenced the deposition of copper ore. The trend of these fracture zones is to the northeast. Southeast along this fracture zone, Potrerillos and Braden may be on the master tectonic feature.

Underlying the area the Andian Batholyth is thought to be present. Scattered exposures of granodiorite and quartz porphyry, which pierce the volcanic andesite and rhyolite and rise above them, often are attributed to it, but their precise relationship is unknown.

III. PORPHYRY-TYPE ORE DEPOSITS

The general features of porphyry-type ore deposits are discussed in this section. Their principal features may be treated under the following headings: mineralogy, host rock types, structure, hydrothermal alteration, and supergene enrichment and oxidation.

A. Ore Mineralogy

The ore mineralogy of the primary zone of most porphyry-type deposits is simple and consists primarily of sulphides. The major sulphides are pyrite, chalcopyrite, and bornite with minor amounts of molybdenite and sphalerite. Deposits which have been leached and enriched by supergene waters exhibit a leached capping from which much of the copper has been removed. The leached copper moves downward to form an enriched layer in which chalcocite and covellite replace the primary sulphide minerals. Molybdenite, due to its relative insolubility, tends to remain in the leached capping where it is mined from some deposits along with copper.

A few examples may be cited to illustrate the mineralogical variations in porphyry deposits. At the San Manuel and Bagdad mines in Arizona, pyrite, chalcopyrite, and bornite are capped by a layer of chalcocite enrichment which, in turn, is buried by a conglomerate. Chrysocolla is the principal oxidized ore mineral.

Ajo, Arizona, exhibits an upper zone of copper carbonate and an underlying primary ore zone which consists of chalcopyrite and minor amounts of bornite and pyrite. Its low pyrite content has inhibited sulphide enrichment.

At the porphyry deposit at Ely, Nevada, the primary ore mineral is chalcopyrite, while at Castle Dome in Arizona there is a disseminated chalcocite deposit with a superimposed copper zone.

Chuquicamata, Chile, the world's largest porphyry deposit, contains primary pyrite, chalcopyrite, enargite, bornite, and molybdenite. Supergene oxide minerals, some of which are unique to Chuquicamata, are: antlerite, atacamite, chalcanthite, krohnkite, brochanthite, natrochalcite, cuprocopiapite, lindgrenite, pisanite, and salesite.

El Salvador, Chile, which is closest to the area in which the writer mapped, exhibits chalcopyrite as the primary ore mineral. Due to the extensive oxidation and secondary enrichment, most of the primary copper sulphide has been converted to chalcocite, but relics of chalcopyrite and bornite occasionally are present. Pyrite is a common gangue sulphide and it may be coated by chalcocite. Near the bottom of the ore body cuprite and native copper are found in veinlets.

B. Host Rock Types

Common host rock types for copper porphyry deposits are monzonite, quartz monzonite, quartz diorite, granodiorite, and the porphyritic varieties of each. Schists and quartzites surrounding the intrusions also may be locally mineralized.

A few specific host rock examples may be cited. Quartz monzonite porphyry is the host rock for the San Manuel, Bagdad, and Castle Dome deposits in Arizona. Monzonite porphyry is the host rock at Ajo, Arizona, and Ely, Nevada. Granodiorite porphyry and diorite porphyry are the host rock at Chuquicamata, Chile. The ores at El Salvador, Chile, occur in four host rocks: granodiorite porphyry, fine-grained granodiorite, quartz porphyry, and andesite.

C. Structure

The acid to intermediate intrusions, which are stock-like to irregular in shape, are often localized by major tectonic features. The upper and outer fractured portions of individual intrusions tend to be most intensely mineralized. The fractures, which may be formed by shrinkage, permitted the rock to be penetrated by mineralizing solutions which deposited quartz and the sulphides.

D. Hydrothermal Alteration

Hydrothermal alteration is present to some degree in all copper porphyry deposits. Alteration products, which accompany mineralization, may include the following: quartz sericite, clays, and chlorite. With increasing intensity of alteration the host rock mafic minerals tend to be destroyed while the outlines of feldspar phenocrysts become increasingly difficult to distinguish. The altered host rock is bleached to a light gray color.

Creasey (1959), applying the phase rule to hydrothermal alteration, indicated three facies characterized by certain minerals. The facies, in order of increasing intensity of alteration, are: propylitic, argillic, and potassium silicate. The propylitic facies is characterized by calcite, montmorillonite, epidote, chlorite, albite, quartz, and apatite. The argillic facies comprises the diagnostic minerals, kaolinite and muscovite. In the potassium-silicate facies, muscovite, biotite, and orthoclase are diagnostic. Each of these facies are subdivided into phases and assemblages.

San Manuel will serve as a typical deposit exhibiting all three facies of alteration. The potassium-silicate facies occurs within the ore deposit and it exhibits the following minerals: sericite, pyrite, and chalcopyrite. At the margins of the ore deposit, the argillic facies consists of sericite and kaolinite which has altered from biotite and plagioclase. Propylitic alteration occurs outside the ore zone and it consists of chlorite and minor amounts of calcite, sericite, and iron oxide. In this facies plagioclase is albitized, while quartz and orthoclase remain unaltered.

E. Oxidation and Supergene Enrichment

Oxidation and supergene enrichment occur in all the porphyry-type deposits to some degree. A schematic cross-section of a typical oxidized and enriched porphyry deposit is illustrated in figure 2. Fully developed vertical layering consists of a leached layer near the surface, an enriched layer and a primary ore.

Oxidized and enriched porphyry deposits have been termed "blanket deposits" because they form huge blankets, usually irregular in shape, and with tops which are parallel to the surface. El Salvador, for example, varies from between 180 feet to 1500 feet. Successive cycles of erosion combined with climatic variations promoted the leaching. Leached rock is characterized by maroon limonite which often is pseudomorphous after chalcocite and other sulphides. Such gossans have been employed as ore guides.

The enriched layer is characterized by chalcocite, covellite and lesser amounts of other secondary sulphides. These secondary supergene minerals occur as disseminations and stock-works in the blanket. At some deposits, such as El Salvador, the principal ore consists of chalcocite, while small amounts of cuprite and native copper occur in the enriched layer. This enrichment layer extends to a depth of 2000 feet at El Salvador, and its upper contact with the oxide layer is sharp. The copper grade abruptly increases in the enriched layer.

The primary ore of porphyry deposits typically consists of pyrite, chalcopyrite, and bornite. These minerals remain unoxidized below the water table.

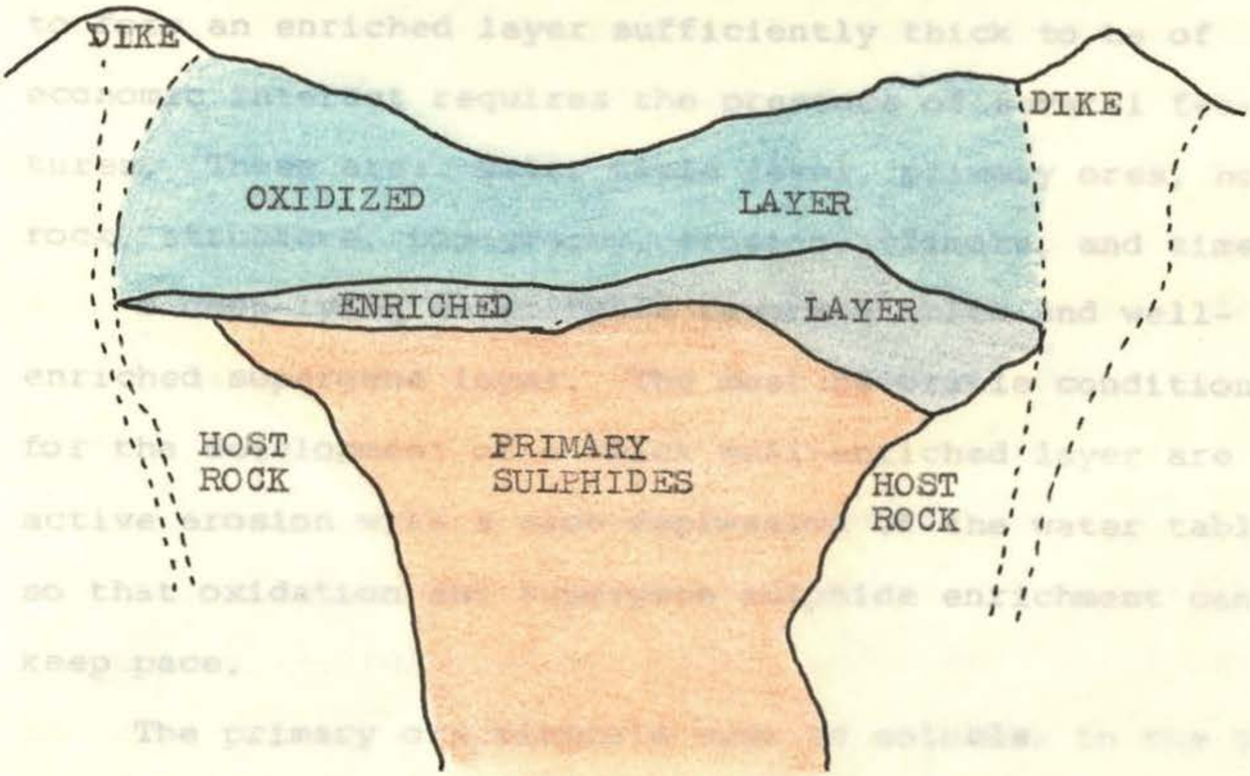


FIG. 2. SCHEMATIC CROSS-SECTION OF A TYPICAL OXIDIZED AND ENRICHED PORPHYRY-TYPE DEPOSIT.

F. Factors Which Influence the Degree of Supergene Enrichment

Supergene enrichment of the primary copper sulphides to form an enriched layer sufficiently thick to be of economic interest requires the presence of several features. These are: water table level, primary ores, host rock, structure, topography, erosion, climate, and time.

A deep-lying water table favors a thick and well-enriched supergene layer. The most favorable conditions for the development of a thick well-enriched layer are active erosion with a slow depression of the water table so that oxidation and supergene sulphide enrichment can keep pace.

The primary ore minerals must be soluble in the supergene solutions. The nature and structure of the host rock must be such as to allow the enriching solutions to percolate through the rocks and attack the primary sulphides.

Faults and particularly fractures of the porphyry host rocks, allow the enriching solutions to penetrate the rock to depth.

A mature topography is most favorable to the development of thick layers of enrichment. In more youthful areas, the rapid erosion tends to remove the enriched layer.

Climatic factors which affect enrichment are temperature and rainfall. High temperatures accelerate enrichment which low temperatures tend to retard. Therefore, enriched layers are generally better developed in warmer climates than in cold climates. Rainfall which is evenly distributed throughout the year promotes enrichment.

The time required to form an enriched layer is the same that is required to produce a mature erosion surface. Such an amount of time is thought by some to constitute the better part of an epoch.

The chemistry of the supergene enrichment of porphyry-type deposits may be treated briefly at this point. Ground water charged with oxygen tend to react with sulphides, particularly pyrite, to form the strong solvents, ferric sulphate and sulphuric acid. These strong solvents may react with sodium chloride yielding hydrochloric acid and the strong oxidizing agent, ferric chloride. The action of these solvents, especially ferric sulphate, upon chalcopyrite, chalcocite and covellite are shown by the chemical reactions below:

$$CuFeS_2 + 2Fe_2(SO_4)_3 \longrightarrow CuSO_4 + 5FeSO_4 + 2S$$

$$Cu_2S + Fe_2(SO_4)_3 \longrightarrow CuSO_4 + 2FeSO_4 + CuS$$

$$CuS + Fe_2(SO_4)_3 \longrightarrow CuSO_4 + 2FeSO_4 + S$$

The copper in solution may then be precipitated as the sulphide, often chalcocite, by one or more of the equations given below.

$$5FeS_2 + 14CuSO_4 + 7H_2O \longrightarrow 7Cu_2S + 5FeSO_4 + 12H_2SO_4$$

$$5CuFeS_2 + 11CuSO_4 + 8H_2O \longrightarrow 8Cu_2S + 5FeSO_4 + 8H_2SO_4$$

$$Cu_5FeS_4 + CuSO_4 \longrightarrow 2Cu_2S + 2CuS + FeSO_4$$

$$5CuS + 3CuSO_4 + 4H_2O \longrightarrow 4Cu_2S + 4H_2SO_4$$

IV. EL SALVADOR "OLD WORKINGS AREA"

A. Petrography and Petrology

Five rock types occur in the El Salvador "Old Workings Area" (see figure 3). From oldest to youngest, they are: rhyolite pebble conglomerate, rhyolite porphyry, andesite, quartz porphyry, and tourmaline-bearing breccia.

1. Rhyolite Pebble Conglomerate

Rhyolite pebble conglomerate is the oldest rock type in the "Old Workings Area," where it constitutes less than five per cent of the exposed rock. While the attitude of the conglomerate is indeterminate in the area mapped, to the west the rhyolite pebble conglomerate commonly weathers to flat-topped outcrops, which Gustafson (1964) believes have developed on bedding planes in the conglomerate. If this is true the conglomerate is nearly horizontal and is more than ten feet thick. The conglomerate pebbles, which are gray to white in color, are predominantly subrounded, but some are well-rounded, as shown in Plate Ia. They range from a few tenths of an inch to as large as six inches in diameter. All the pebbles examined by the writer are rhyolitic in composition. Thus, rhyolite must lie stratigraphically beneath, as well as above the conglomerate. The rhyolite pebbles are very similar in mineralogy and texture to the rhyolite discussed in the following section. These pebbles are cemented by a green matrix, whose green color is due to abundant extremely fine-grained secondary epidote. Xenocrysts of relatively unaltered feldspar also occur in the

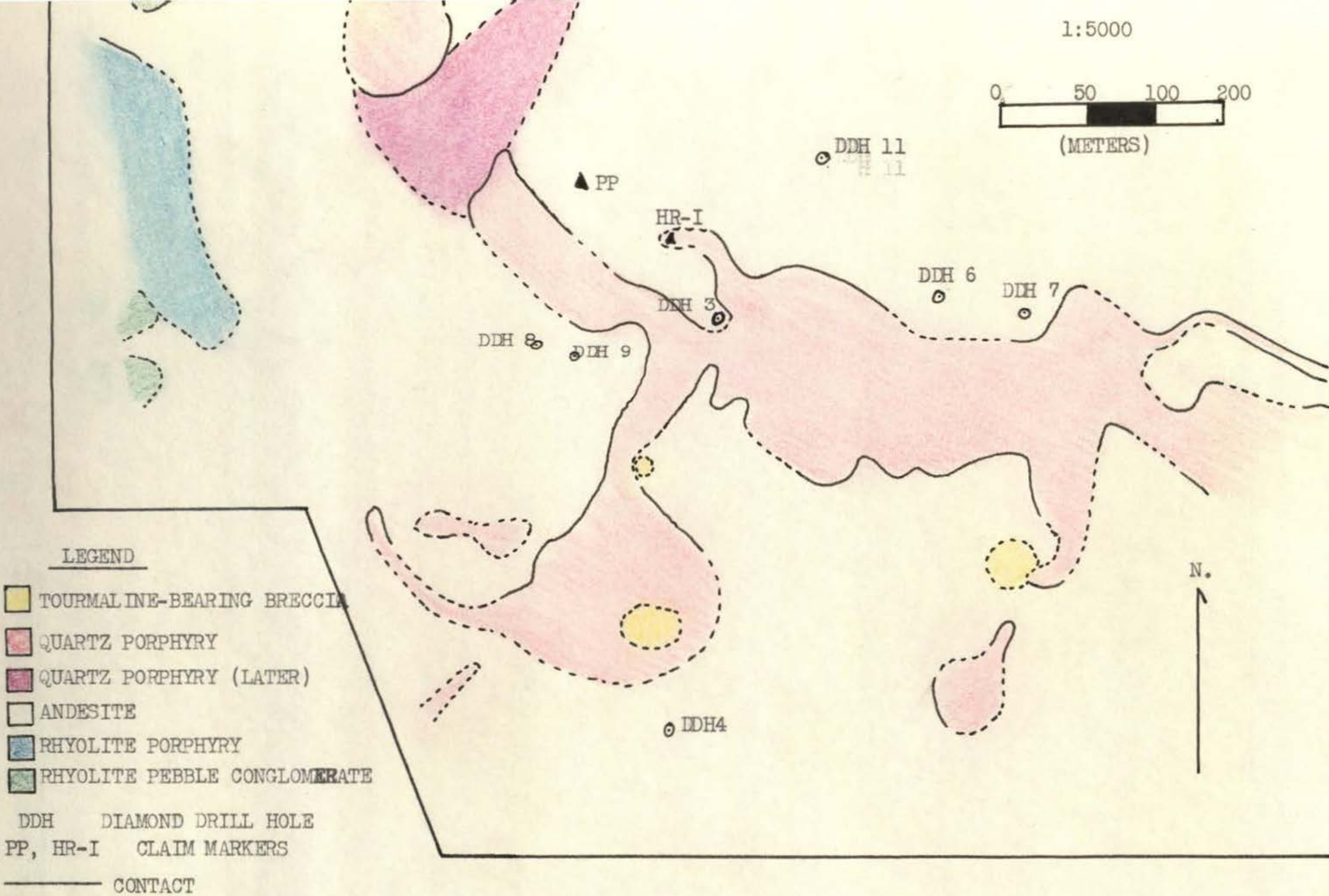


FIG. 3. GEOLOGIC MAP OF " OLD WORKINGS AREA"

matrix. All the xenocrysts are subrounded and they have an average size of eighty microns. Many exhibit well developed polysynthetic twinning.

Matrix constituents of the rhyolite pebble conglomerate are secondary epidote, orthoclase, plagioclase, and clay material. The epidote is concentrated into irregular areas about 1.2 millimeters in diameter, in which the individual epidote grains are fifty microns. Epidote is confined to the matrix, where it constitutes about fifteen percent of the rock.

Orthoclase xenocrysts, which are mostly less than twenty microns in size, are rounded to subrounded. The disseminated grains are readily revealed by the yellow sodium cobalt-nitrite stain.

Plagioclase phenocrysts also are subrounded. They may be as large as one millimeter, but they have an average size of eighty microns. Some grains are partly altered to sericite, but most exhibit well developed polysynthetic twinning.

A fine-grained component of the cementing matrix, which exhibits a first order gray interference color, is thought to be clay. The grains are less than two microns and they are scattered throughout the matrix.

Since the cementing matrix is similar in composition to the rhyolite pebbles, some have considered the rock to be a volcanic agglometare. The writer believes this rock to be a conglomerate, for all fragments show rounding.

2. Rhyolite Porphyry

Rhyolite flows, which are horizontal in attitude, occur above the conglomerate, for rhyolite can be seen to overlie the conglomerate where they are in contact along the western edge of the "Old Workings Area." The rhyolite is about twenty feet thick. The light gray rhyolite contains green spots of epidote which are aligned in certain planes. Phenocrysts of quartz and plagioclase, which rarely are observed with the naked eye, are seen with the aid of the microscope to constitute about thirty per cent of the porphyritic rock.

The major phenocrysts, plagioclase and quartz, are scattered throughout the rock. The plagioclase phenocrysts, which comprise five per cent of the rock, are euhedral to subhedral, and they often are broken. While they may be as large as 0.6 millimeter in diameter, they are more commonly about 0.2 millimeter. The smaller plagioclase phenocrysts are completely altered to sericite, but the larger phenocrysts are only slightly altered and often exhibit polysynthetic twinning. Quartz phenocrysts, which comprise twenty per cent of the rock, are subhedral to nearly euhedral. Some are as large as 0.2 millimeter, but most are about eighty microns. Quartz phenocrysts commonly are embayed by the groundmass.

The phenocrysts are set in a groundmass (see Plate Ib) composed of orthoclase, quartz, plagioclase, and secondary epidote.

Groundmass orthoclase grains are subhedral to nearly

Plate Ia. Photomicrograph of rhyolite pebble conglomerate showing a rounded pebble in a cementing matrix of secondary epidote, orthoclase, plagioclase, and clay. Nicols crossed. (30X)

Plate Ib. Photomicrograph of rhyolite porphyry exhibiting porphyritic texture. Phenocrysts of plagioclase and quartz in a matrix of orthoclase, quartz, plagioclase and secondary epidote. Nicols crossed. (30X)

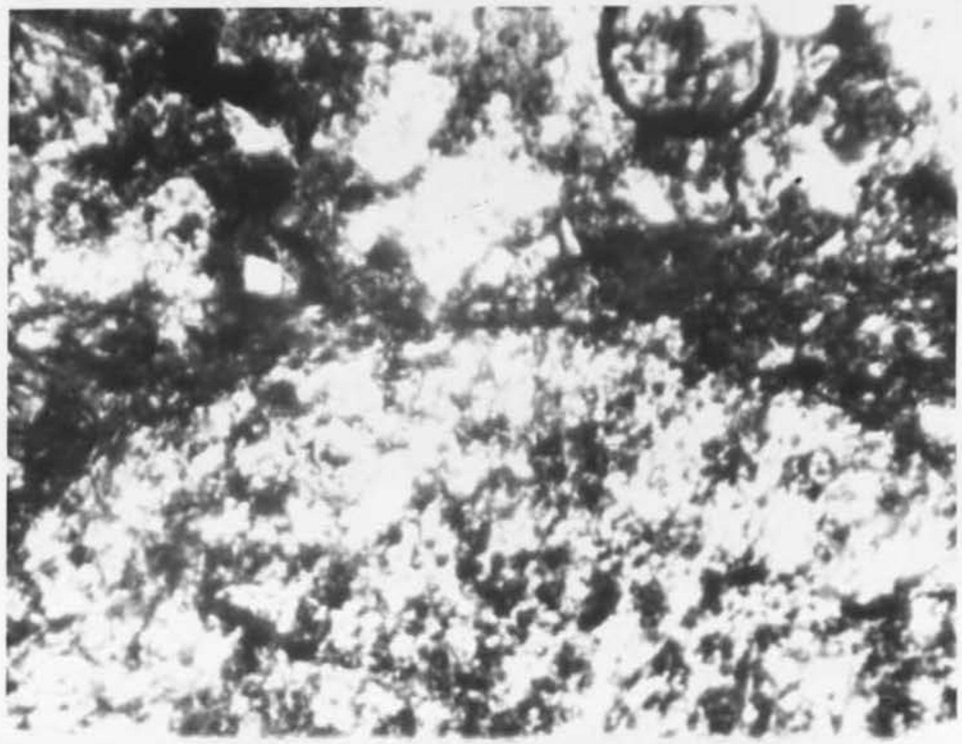
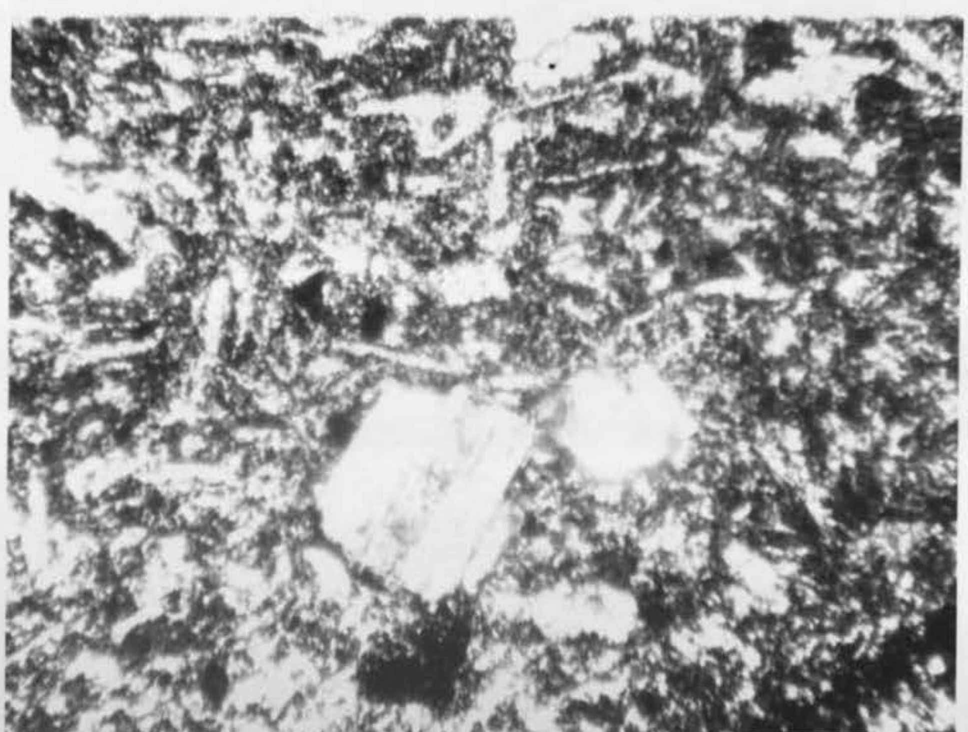


Plate Ia

Plate Ib



euhedral, and they average less than ten microns. Sodium cobalt-nitrite yellow staining revealed disseminated grains of orthoclase and demonstrated that orthoclase is concentrated around the epidote areas. Orthoclase comprises sixty-five per cent of the rock.

Plagioclase microlites constitute fifteen per cent of the groundmass. The microlites are irregular in shape and smaller than forty microns. They are partly altered to sericite.

Areas of secondary epidote are as large as 2.5 millimeters, but are more commonly about one millimeter. Each irregularly shaped area is formed by a cluster of individual epidote grains which have an average grain size of forty microns, and the areas frequently contain centrally located quartz grains of about twenty microns in size. Isolated epidote grains are disseminated elsewhere in the groundmass. Epidote areas comprise thirty-five per cent of the rock. Secondary dendritic manganese oxides and coatings of iron oxide occur as fracture planes in the rhyolite porphyry.

3. Andesite

Andesite flows, which are horizontal in attitude, occur above the rhyolite flows and the contact between the two rock units is exposed in the northwestern portion of the mapped area. The andesite, which is more than fifty feet thick, constitutes about fifty-five per cent of the mapped area. It is light colored and no phenocrysts are visible to the naked eye, but this may be due to the intense alteration (see Plate IIa). Microscope examination of the rock indicates that its original texture was equigranular.

The rock originally consisted principally of feldspar, presumably plagioclase. These irregular feldspar ghosts, which are about forty microns in size, are aligned parallel to flow structure. The feldspar now is completely altered to sericite and clay. While staining with sodium cobaltnitrite did not detect orthoclase, this may be due to the intense feldspar alteration. Irregular grains of quartz, about forty microns in size, are very sparsely scattered through the rock.

The intensely altered andesite now consists of the secondary minerals, sericite and clay as shown in Plate IIb. Sericite, which comprises sixty-five per cent of the rock, is platy and occurs in clusters about forty microns in size. The clay material is characterized by a very fine-grained size of one to two microns and by a first order gray interference color. It comprises thirty-five per cent of the rock. Secondary quartz occurs in veinlets, eighty microns in width, which pervade the entire rock, as shown in Plate IIIa. Many fractures contain gypsum and iron oxide stains (see Plate IIIb).

4. Quartz Porphyry

The quartz porphyry, which appears to be irregular in shape, intruded the andesite as shown by its areal distribution and cross-cutting nature (see Plate IVa) and by apophyses intersected in drill core, as well as by its

Plate IIa. Photomicrograph of andesite exhibiting clay (dark gray) and sericite (light gray) formed by alteration of plagioclase and other minerals. Crossed nicols. (30X)

Plate IIb. Photograph showing intense alteration (light gray) of andesite (medium gray).

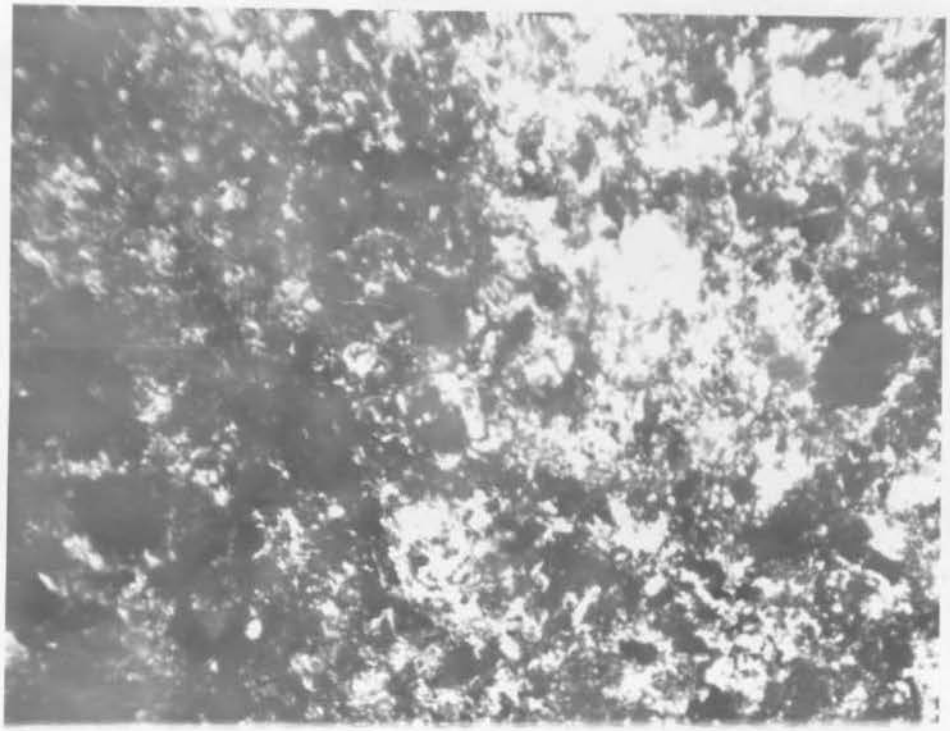


Plate IIa

Plate IIb

Plate IIIa. Photograph showing abundant fractures in andesite which have been filled by secondary quartz.

Plate IIIb. Photograph of intensely fractured andesite. Dark areas are caused by secondary iron oxide.

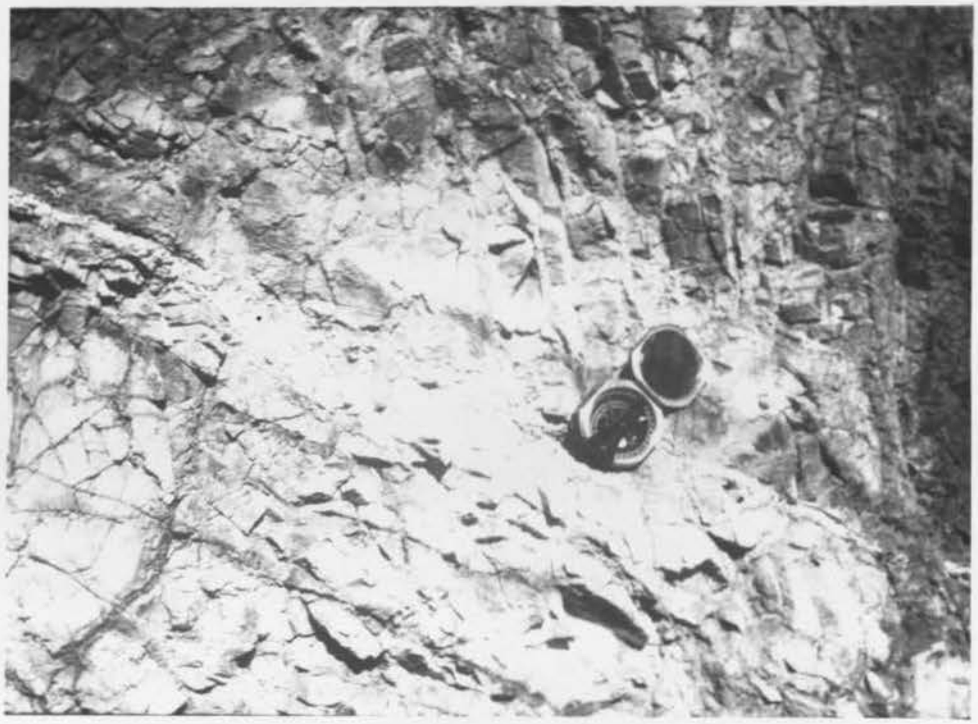


Plate IIIa

Plate IIIb

Plate IV. Photograph showing contact of quartz porphyry (left) intrusive into andesite (right). Alteration and mineralization are prevalent along the contact.

Plate IV.

texture. Thirty-five per cent of the mapped surface is quartz porphyry. The texture of the rock is porphyritic and phenocrysts of quartz, plagioclase, hornblende, and muscovite can be seen with the naked eye. Microscopic examination reveals a holocrystalline groundmass consisting of quartz plagioclase, and secondary sericite, clay, and chlorite.

The clear and unaltered disseminated quartz phenocrysts are subhedral to nearly euhedral. Some are as large as five millimeters, but the average is close to two millimeters. About one-half of the phenocrysts show embayment by matrix material which crosses as much as one-third the width of some phenocrysts. Quartz porphyry from drill holes suggests that the size and abundance of the quartz phenocrysts increases with depth. Quartz phenocrysts comprise fifteen per cent of the rock.

Plagioclase phenocrysts are scattered, subhedral to nearly euhedral, average about three millimeters, but some are as large as seventeen millimeters; their size increases with depth. Many phenocrysts are zoned and some zones exhibit greater alteration than others. Other phenocrysts exhibit polysynthetic twinning and some carlsbad twinning. The plagioclase phenocrysts are completely altered to secondary minerals in all of surface quartz porphyry specimens collected by the writer.

Irregular to rounded phenocrysts of hornblende have an average grain size of 0.2 millimeter. These disseminated phenocrysts show alteration rims of chlorite. Hornblende phenocrysts are rare.

Lath-like crystals of muscovite may be as large as 0.3 millimeter, but more commonly they are eighty microns. Muscovite is scattered throughout the rock and exhibits alteration to clay. Muscovite is also rare.

The groundmass constituents of the quartz porphyry originally were quartz, orthoclase, and plagioclase. They are subhedral to nearly euhedral and about forty microns is size. Surface samples have a matrix grainsize of less than ten microns (see Plate Va) while quartz porphyry matrix in the deepest drilling is about twenty microns (see Plate Vb).

Among the secondary minerals in quartz porphyry, sericite and clay are the most abundant. Sericite has an average grain size of less than two microns, but some are as large as ten microns. The clusters of sericite are scattered throughout the rock, but they are most abundant in the former sights of plagioclase and orthoclase phenocrysts. Clay material has an average size of about one micron and it too is concentrated in areas of former phenocrysts. Sericite and clay together comprise about sixty per cent of the average quartz porphyry.

Surface samples of the rock exhibit holes where the feldspar crystals have weathered out.

5. Tourmaline-Bearing Breccia

Tourmaline-bearing breccia intrudes the quartz porphyry and andesite, and it comprises less than five per cent of

Plate Va. Photomicrograph of quartz porphyry showing two subhedral quartz phenocrysts (black, top) and a plagioclase phenocryst ghost (top) now altered to sericite and clay. The phenocrysts are set in a fine-grained groundmass. Note the embayment of one quartz phenocryst. Also compare the size of the groundmass of this Plate and Plate Vb. Crossed nicols. (30X)

Plate Vb. Photomicrograph of quartz porphyry obtained in a diamond drill hole. Note the larger grain size of the quartz and orthoclase in the groundmass of this specimen as contrasted to that of quartz porphyry above which was collected on the surface. Crossed nicols. (30X)

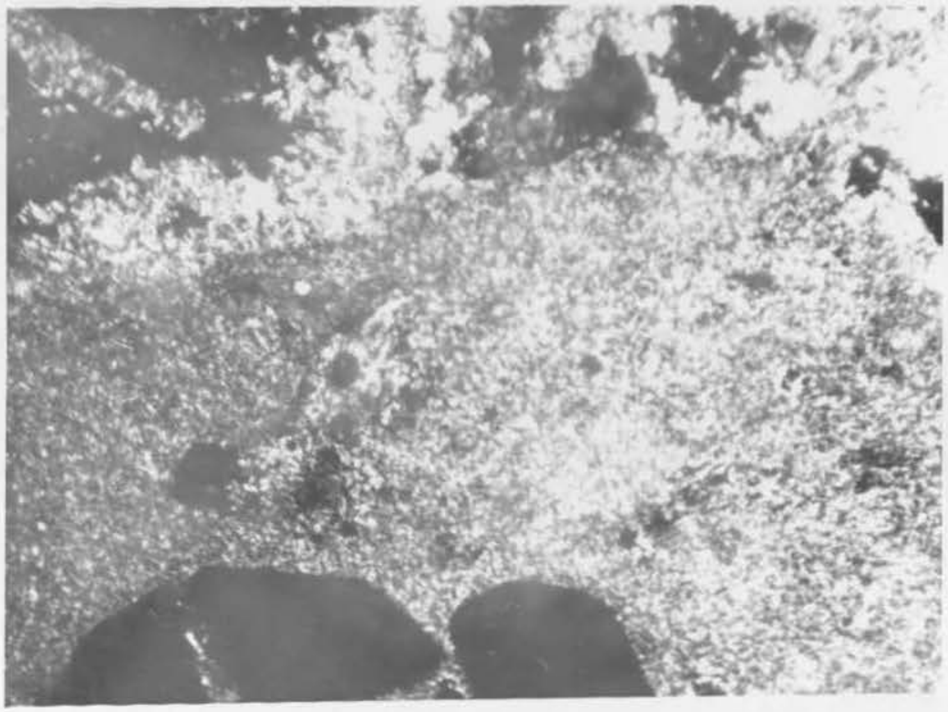


Plate Va

Plate Vb

the mapped area. Three pipes were mapped in the "Old Workings Area." Their diameters, from largest to smallest, at the surface are: forty-five meters, thirty-meters, and ten meters respectively. One pipe cuts quartz porphyry at the surface, while the other two penetrate andesite. Since the quartz porphyry is known to dip beneath the andesite, quartz porphyry probably is intruded at depth by all three tourmaline-bearing breccia pipes. The fragments are mostly quartz porphyry, but some are andesite. They are angular to subangular (see Plate VIa) and may be as large as three meters, but usually they are several centimeters in size. These light colored fragments are cemented by a dark aphanitic matrix.

The matrix can be seen with the microscope to consist of twenty per cent quartz and eighty per cent tourmaline. The quartz is subhedral to nearly euhedral and about two microns in grain size. The quartz is penetrated by long thin tourmaline prisms, ten to fifteen microns long and one to two microns wide. The tourmaline crystals were deposited upon the breccia fragments and they grew outward in radial groups into open spaces, where they form comb-like structures, as shown in Plate VIb. Large quartz grains were deposited at the same time or later than the tourmaline.

B. Ores

In the "Old Workings Area" primary sulphide minerals are pyrite, chalcopyrite, and molybdenite. The secondary

Plate VIa. Photograph of tourmaline-bearing breccia showing quartz porphyry and andesite breccia fragments (light gray) cemented by a quartz-tourmaline matrix (dark gray).

Plate VIb. Photomicrograph showing tourmaline crystals (medium gray, long) and quartz grains (light gray) cementing breccia fragments (dark gray). Crossed nicols. (30X)

Plate VIa

Plate VIb

sulphide minerals are chalcocite and covellite; brochanthite and antlerite are present as secondary copper sulphates and chrysocolla is present as a secondary copper silicate. Copper Pitch found in the area consists of hausmannite and braunite.

1. <u>Primary Sulphide Minerals</u>

Of the primary sulphide minerals, pyrite occurs in quartz porphyry, rhyolite pebble conglomerate, and tourmaline-bearing breccia, while chalcopyrite is present in the rhyolite pebble conglomerate and quartz porphyry and molybdenite appears to be restricted to the quartz porphyry.

a. <u>Pyrite</u>

Cubic and rounded to irregular grains of pyrite occur in veins and as disseminations throughout the three rock types indicated above (see Plate VIIa). The grains are 0.2 millimeter in the conglomerate. Pyrite in the quartz porphyry is locally surrounded by iron staining. Pyrite comprises as much as ten per cent of some quartz porphyry and conglomerate specimens and fifteen per cent of some tourmaline-bearing breccia specimens.

b. <u>Chalcopyrite</u>

Chalcopyrite occurs in the conglomerate, where it fills cracks in pyrite veins. Disseminated irregular grains of chalcopyrite occur in quartz porphyry and conglomerate (see Plate VIIb). As much as one per cent chalcopyrite was observed in some polished surfaces of quartz porphyry while as much as three per cent chalcopyrite is present in some

Plate VIIa. Photomicrograph of quartz porphyry showing abundant pyrite and one grain chalcocite. Reflected light. (30X)

Plate VIIb. Photomicrograph of rhyolite pebble conglomerate showing that chalcopyrite formed after pyrite. Reflected light. (30X)

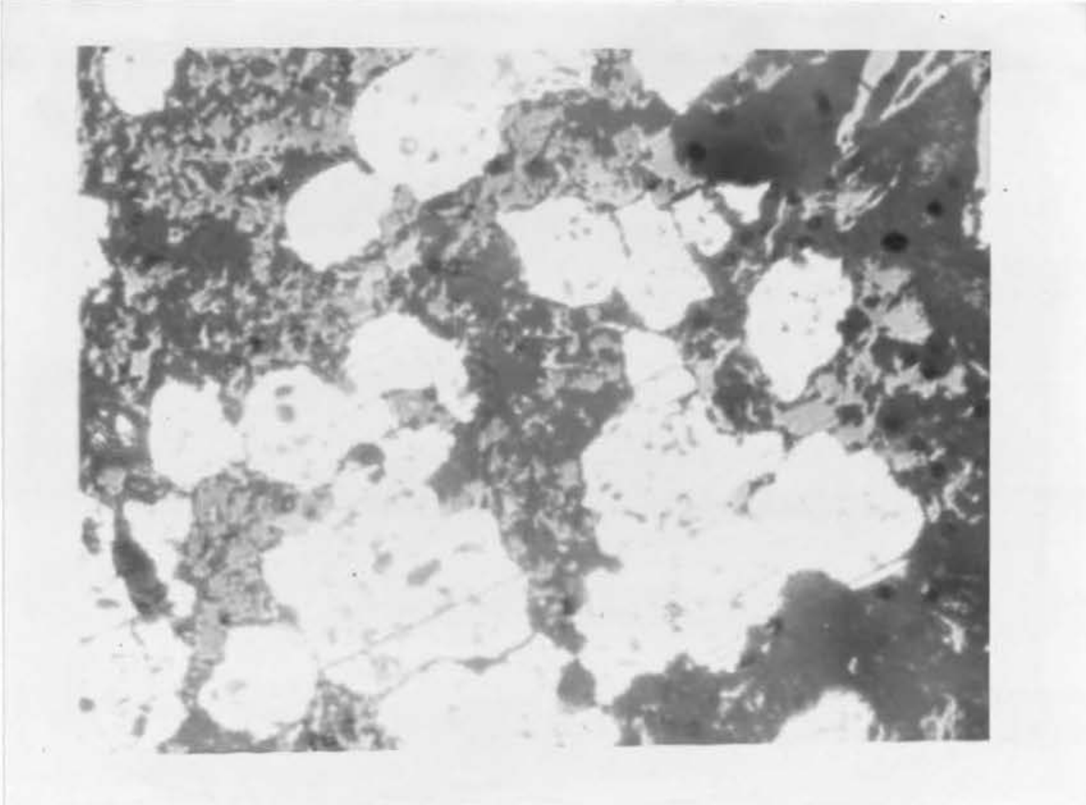
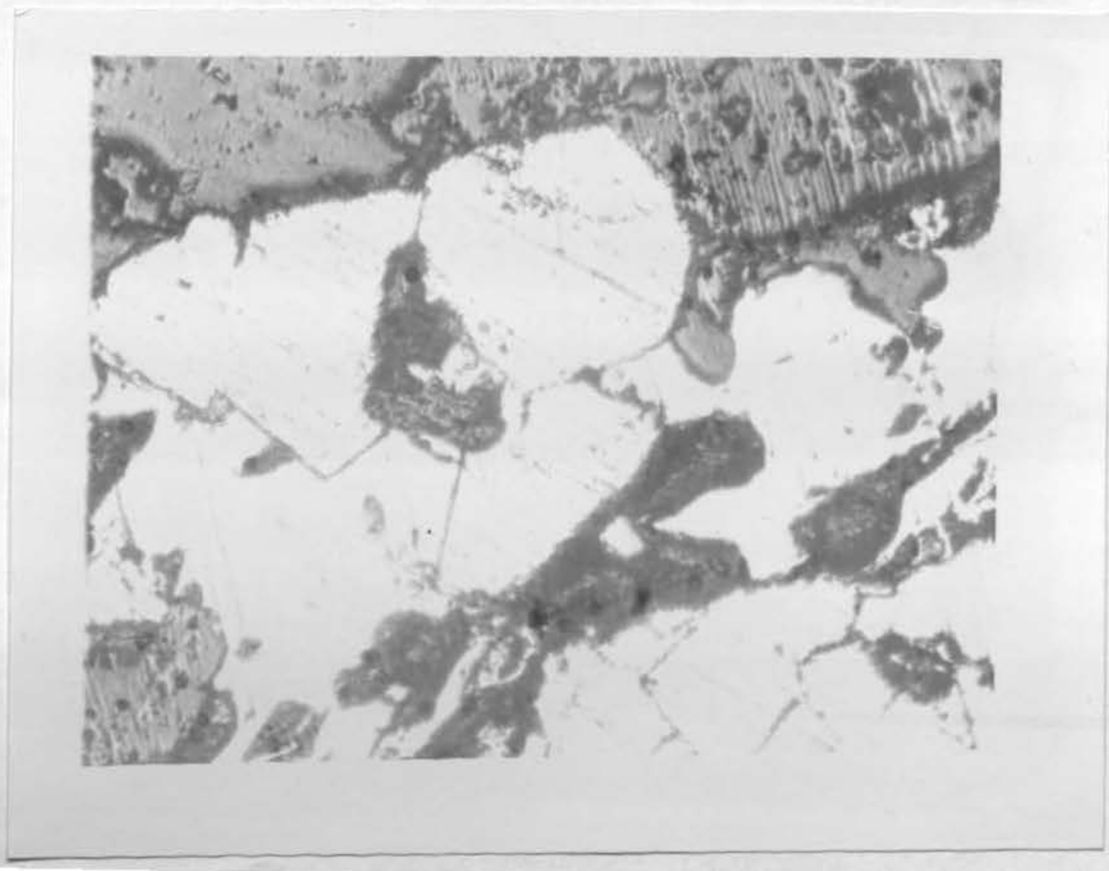


Plate VIIa

Plate VIIb



specimens of conglomerate. The disseminated grains are about 0.1 millimeter in the conglomerate and forty microns in the quartz porphyry. Chalcopyrite exhibits ice cake texture with some pyrite (see Plate VIIIa) in veins after pyrite grains indicating that it formed later than the pyrite which it has replaced.

c. Molybdenite

Tabular crystals of molybdenite are sparcely scattered in the quartz porphyry and in conglomerate where they have an average size of forty microns. They are characterized by their tabular shape and very strong anisotropism. One crystal adjacent to pyrite suggests that molybdenite formed first. Molybdenite comprises less than one per cent of both rock units.

2. Secondary Sulphide Minerals

Secondary sulphide minerals formed in the "Old Workings Area" are chalcocite and covellite. Where covellite. Where covellite is formed, it is intimately intergrown with chalcocite.

a. Chalcocite

Irregularly shaped chalcocite is disseminated in the conglomerate and tourmaline-bearing breccia. In the quartz porphyry, chalcocite is associated with pyrite and covellite. That chalcocite has replaced pyrite is shown by the occassional ice cake texture.

b. Covellite

Covellite occurs only in quartz porphyry, where it is associated with chalcocite as intimate intergrowths, which may have formed by unmixing from solid solution or perhaps by replacement. The irregular grains have a size less than one micron. These grains are always intergrown with chalcocite. Covellite comprises less than one tenth of a per cent of quartz porphyry specimens examined by the writer.

3. <u>Secondary Sulphate and Silicate Copper Minerals</u>

The secondary sulphate minerals, brochanthite and antlerite, and secondary copper silicate, chrysocolla, occur in quartz porphyry in the "Old Workings Area." Megascopic identifications of these minerals were checked in selected oil immersions under the polarizing microscope.

Brochanthite occurs as emerald green, loosely coherent aggregates of acicular crystals in groups, drusy crusts, and granular disseminations. These transparent to translucent crystals have a vitreous luster. Brochanthite comprises about forty per cent of the oxidized copper mineralization.

Antlerite occurs as cross fiber veinlets and friable interlaces aggregates of fibrous crystals. These crystals are blackish green and exhibit a vitreous luster. Antlerite has a slightly lower index and lower birefringence than does brochanthite. Antlerite comprises about twenty per cent of the surface copper minerals.

Earthy chrysocolla occurs as incrustations and veins. Its bluish green color and earthy luster are diagnostic. With the aid of the microscope chrysocolla can be seen to have a low index of refraction and frequently colloform texture. Chrysocolla comprises forty per cent of the oxidized copper minerals.

4. Miscellaneous

Irregular hematite grains are present in the quartz porphyry in areas that are highly iron stained. The average size of these grains is forty microns and they occur as disseminations and veinlets.

Copper Pitch occurs south of the "Old Workings Area" in a small vug about two meters in diameter and one-half meter deep. It occurs as a dull earthy black manganese oxide material on andesite.

The material, when studied under the microscope, exhibits abundant quartz veins crossing altered andesite. The individual quartz grains which are about forty microns, are surrounded by later manganese oxide. The clay and sericite of the altered andesite absorbed the manganese oxide and iron oxide. It appears the andesite was altered, quartz veining was introduced with manganese and copper mineralization and then the rock was oxidized.

The polished section study of the black opaque material indicated the minerals hausmannite and braunite (see Plate VIIIb). Hausmannite is gray with a slight brownish tint, and some grains exhibit a reddish brown internal reflection. It has strong anisotropism and it exhibits lamellar twinning. Braunite displays a similar color and lower hardness to that of hausmannite, but its anisotropism is weaker than that of hausmannite. The mineral is granular and does not exhibit internal reflection.

Plate VIIIa. Photomicrograph of ice cake texture between pyrite and chalcopyrite, in-dicating that chalcopyrite has replaced pyrite. Reflected light. (30X)

Plate VIIIb. Photomicrograph of copper pitch showing hausmannite surrounded by braunite. Reflected light. (30X)

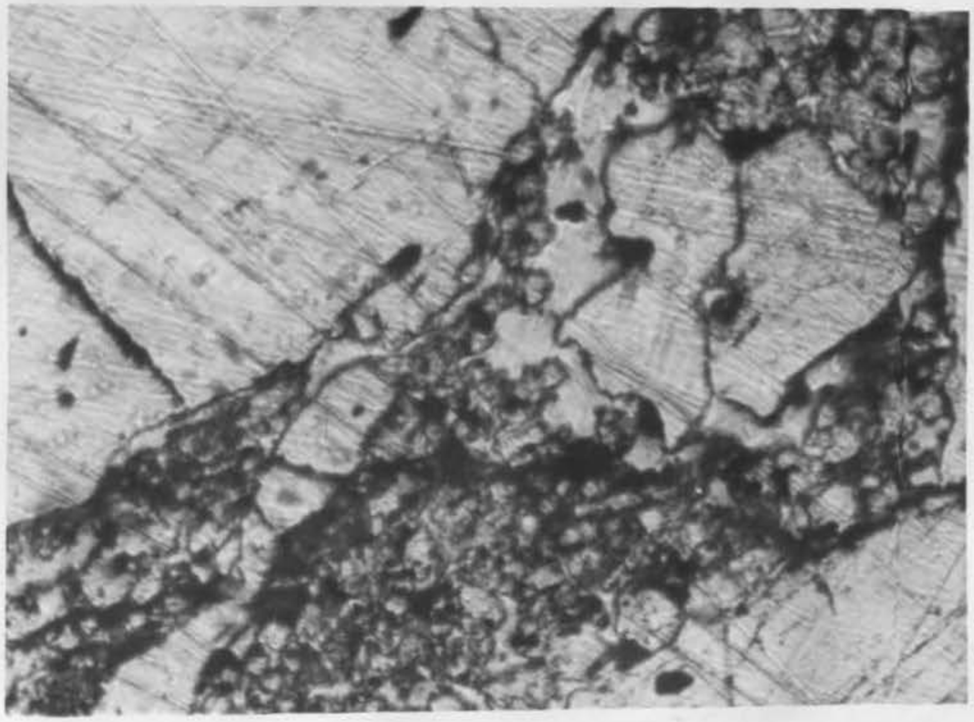
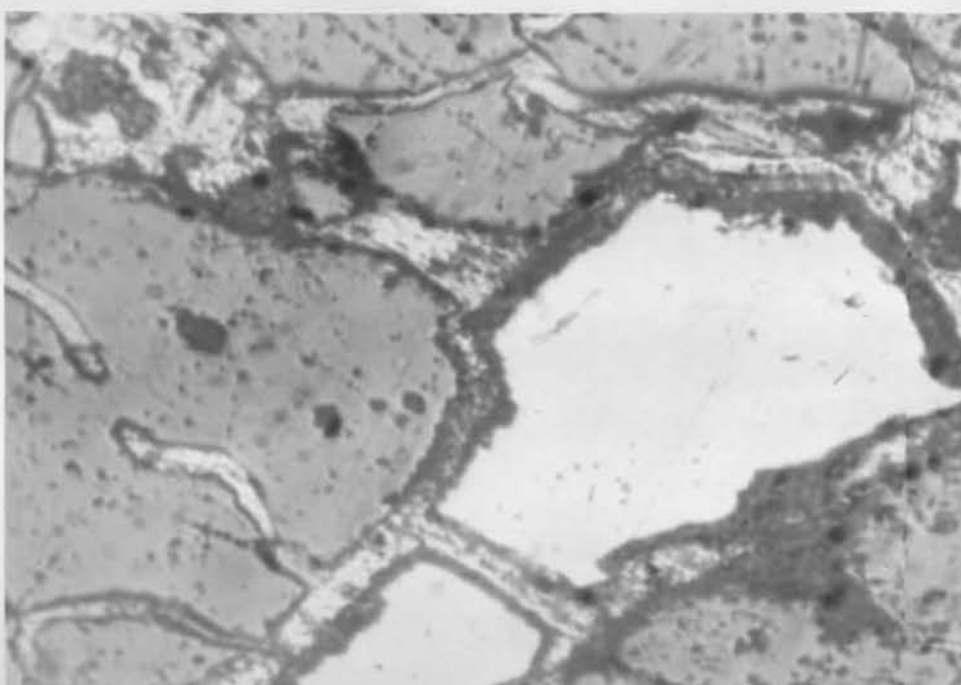


Plate VIIIa

Plate VIIIb



V. SUMMARY AND CONCLUSIONS

Five rock types were mapped in the "Old Workings Area". These rock types, from oldest to youngest are rhyolite pebble conglomerate, rhyolite porphyry, andesite, quartz porphyry, and tourmaline-bearing breccia. In terms of abundance, the mapped area comprises fifty-five per cent andesite, thirty-five per cent quartz porphyry, and ten per cent rhyolite pebble conglomerate, rhyolite porphyry, and tourmaline-bearing breccia.

The quartz porphyry intruded the andesite as an chonolith while tourmaline-bearing breccia intruded in the form of a pipe. Three tourmaline-bearing breccia pipes occur in the mapped area. The rhyolite pebble conglomerate appears to be horizontal and has a thickness of more than ten feet. The horizontal rhyolite porphyry is about twenty feet in thickness, while the flat-lying andesite is approximately fifty feet thick.

By petrographic examination the mineralogy and texture was determined for each of the five rock types. The rhyolite pebble conglomerate to be composed of rhyolite pebbles in a cementing matrix of the same composition. The rhyolite porphyry flows, as well as the rhyolite pebble conglomerate, consist of orthoclase, plagioclase, quartz, and hornblende phenocrysts in a fine-grained groundmass of quartz and orthoclase. The andesite flow, originally consisted of andesine plagioclase, hornblende, and very minor quartz. The least altered quartz porphyry consists of phenocrysts of quartz, andesine plagioclase, and hornblende in a fine-grained groundmass of quartz, orthoclase, and plagioclase. The tourmaline-bearing breccia consists of fragments of quartz porphyry and andesite in a matrix of quartz and tourmaline.

The rocks in the "Old Workings Area" are intensely altered by hydrothermal solutions. This is attested to by the presence of secondary alteration products and introduced secondary minerals: quartz, sericite, chlorite, epidote, and sulphides. Biotite, which normally is the first mineral to be attacked, is altered to muscovite. The feldspars are intensely altered to sericite and clay minerals, while hornblende is completely altered to chlorite. Secondary quartz veinlets are abundant in the altered rocks. The most intense alteration surrounds the quartz porphyry intrusives and it decreases in intensity outward.

The primary sulphides were found to occur in three of the five mapped rock units: quartz porphyry, tourmaline-bearing breccia, and rhyolite pebble conglomerate. With the aid of the ore microscope, pyrite was found to be most abundant in the tourmaline-bearing breccia, but also to occur in quartz porphyry and rhyolite pebble conglomerate. Other sulphides found to occur in these three rock types, in order of abundance, are: chalcopyrite, chalcocite, molybdenite, and covellite.

The action of weathering is attested to by the prevently iron oxide staining of the rocks in the mapped area.

Weathering has probably contributed to the alteration of the surface specimens collected by the writer, for they are more altered than drill core from depth. How much alteration is due to hydrothermal solutions and how much is due to weathering has been difficult to determine in the present study.

Surface oxidation has formed an oxidized layer in which brochanthite, antlerite, and chrysocolla are present. These secondary minerals are most abundant on the surface in the "Old Workings Area".

VI. BIBLIOGRAPHY

A. References Cited

Creasey, J. C. (1959), Hydrothermal Alteration, Econ. Geol., vol. 54, no. 3, pp. 351-373.

Cristi, J. M. (1959), Chile, Geol. Soc. Amer. Mem. 65, pp. 189-214.

Emmons, R. C. (1959), The Universal Stage, Geol. Soc. Amer. Memoir 8, pp. 115-133.

Gustafson, (1964), Personal Communications.

Harrington, H. J. (1961), Geology of Antofagasta and Atacama Provinces, Northern Chile, Amer. Assoc. Petrol. Geol. Bull., vol. 45, no. 2, pp. 169-197.

Kents, P. (1961), Origin of Porphyry Breccias, Econ. Geol., vol. 56, no. 8, pp. 1465-1469.

Kents, P. (1964), Special Breccias Associated with Hydrothermal Developments in the Andes, Econ. Geol., vol. 59, no. 8, pp. 1551-1563.

Swayne, Trask (1960), El Salvador Development, Mining Engineering, April, pp. 6-10.

B. Other References

Anderson, C. A. (1950), Alteration and Metallization in the Bagdad Porphyry Copper Deposit, Arizona, Econ. Geol., vol. 45, pp. 609-628.

Burnham, C. W. (1962), Facies and Types of Hydrothermal Alteration, Econ. Geol., vol. 57, pp. 768-784.

Gilluly, J. (1946), The Ajo Mining District, Arizona, U.S. Geol. Surv. Prof. Paper 209.

Kerr, P. F. (1951), Alteration Features at Silver Bell, Arizona, Geol. Soc. Amer. Bull., vol. 62, pp. 451-480.

Kerr, P. F. and others (1950), Hydrothermal Alteration at Santa Rita, New Mexico, Geol. Soc. Amer. Bull., vol. 61, pp. 275-347.

Leroy, P. G. (1954), Correlation of Copper Mineralization with Hydrothermal Alteration in Santa Rita Porphyry Copper Deposits, New Mexico, Geol. Soc. Amer. Bull., vol. 65, pp. 739-768.

Lopez, V. M. (1939), The Primary Mineralization at Chuquicamata, Chile, South America, Econ. Geol., vol. 36, pp. 674-711.

McCartney, W. D. (1962), Mineralization in Mobile Belts, Econ. Geol., vol. 57, no. 7, pp. 1131-1132.

Perry, Vincent D. (1961), The Significance of Mineralized Breccia Pipes, Mining Engineering, April and Am. Inst. Mining, Met. and Pet. Eng. Trans., vol. 220, pp. 216-226.

Peterson, N. P.; Gilbert, C. M.; Quick, G. L. (1946), Hydrothermal Alteration in the Castle Dome Copper Deposit, Arizona, Econ. Geol., vol. 41, pp. 820-840.

Schwartz, G. M. (1947), Hydrothermal Alteration in the Porphyry Copper Deposits, Econ. Geol., vol. 42, pp. 319-352.

Stringham, B. (1958), Relationship of Ore to Porphyry in the Basin and Range Province, U.S.A., Econ. Geol., vol. 53, pp. 806-821.

Stringham, B. (1953), Granitization and Hydrothermal Alteration at Bingham, Utah, Geol. Soc. Amer. Bull., vol. 64, pp. 945-992.

Stringham, B. (1960), Porphyry Copper, Econ. Geol., vol. 55, no. 8, pp. 1622-1630.

VITA

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He graduated from Irondequoit High School in Rochester, New York, in 1959. Upon graduation from high school he enrolled at St. Lawrence University where he received a Bachelor of Science Degree in Geology in June, 1963. Throughout his four years at St. Lawrence University he prepared mineral and rock collections for colleges and universities at Ward's Natural Science Establishment.

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