GEOLOGY AND ORE DEPOSITS OF THE WALLAPAI DISTRICT, ARIZONA

Thesis by

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ABSTRACT

The Wallapai district is in the Cerbat Mountains, a range composed chiefly of crystalline rocks that are pre-Cambrian in age. The oldest rocks are quartzite, mica schist, hornblende-diopside schist, and amphibolite. Younger and larger in amount are granite gneiss and granite. Much of the gneiss is believed to be a product of granitization. Gabbroic and dioritic gneiss, pegmatite, aplite, diabase, and mylonite also occur as part of the basement complex. The original rocks were disposed in an orogenic fold system, but igneous intrusion and granitization have obliterated all but a few remnants of the folds. The rock types and the pre-Cambrian history are similar to those of the Grand Canyon area.

The region contains no trace of Paleozoic rocks and probably none of Mesozoic age. Intrusions of granite porphyry in the Chloride and Mineral Park districts are believed to be Tertiary in age. Granite porphyry, pegmatite, aplite, and lamprophyre dikes are associated with these intrusions.

Small areas of andesitic and rhyolitic extrusive rocks, presumably of Tertiary age, exist along the flanks of the Cerbat Range. Thin sheets of Quaternary basalt cap these rocks along the west side of the range. This basalt also lies on and interfingers with alluvium. Numerous rhyolite dikes and a few andesite and basalt dikes occur within the basement rocks.

Several periods of faulting and erosion are visible in the volcanic rocks. The latest faulting is of basin-range type and has outlined and caused the elevation of the present mountains. The greatest displacement has been on the west side, and the Cerbat Range is an eastward tilted fault block, modified in part into a horst. This mountain building seems to have occurred in late Tertiary and Quaternary time. Large quantities of detritus have accumulated in the adjoining basins, and a pediment has been cut along the base of the range. Recent fault-block movement is suggested by the presence of terraces within the canyons and by the dissection of the pediment at the west base of the range.

Mineralization is believed to have occurred after the close of Tertiary volcanic activity. The first phase consisted of "porphyry copper" mineralization in a strongly shattered portion of the granite porphyry stock in the Mineral Park district. This was succeeded by the profuse formation of fissure veins, which carry the lead-zinc ores of the region. The veins are superimposed upon and grouped symmetrically around the "porphyry copper" mineralization. Tectonic action is postulated as the fundamental control for the emplacement of the granite porphyry stock and for the two types of sulfide mineralization that are areally associated with the stock. Turquoise deposits have developed by supergene processes in the capping of the "porphyry copper" deposit.

A late fault cuts the alluvium west of the Mineral Park district. This fault and the adjacent alluvial blanket have been mineralized by chrysocolla and form the Emerald Isle copper deposit. The chrysocolla is believed to be hypogene in this deposit.

INTRODUCTION

LOCATION, CULTURE AND ACCESSIBILITY

The Wallapai district is located in Mohave County, in the extreme northwest portion of Arizona (see Figure 1). It is largely within the Chloride quadrangle, which is bounded by meridians 114 degrees and 114 degrees 15 minutes west, and parallels 35 degrees 15 minutes and 35 degrees 30 minutes north. The town of Kingman is approximately 5 miles due south of the quadrangle. Hoover Dam is approximately 50 miles to the northwest.

The only town in the area is Chloride (see Figure 2), center of the Chloride mining district. This town, which has a population of a few hundred and the only post office in the quadrangle, is located in the northwest section of the quadrangle, 20 miles from Kingman. Successively to the south of the Chloride district are the Mineral Park, Stockton Hill, and Cerbat districts. Once fairly populous, they are now largely deserted. Collectively, these four districts constitute what is known as the Wallapai or Hualpai mining district. A few scattered ranch houses are the only habitations outside the mining areas.

U. S. Highway Numbers 93 and 466, the route between Kingman and the Hoover Dam, cuts across the southwest section of the quadrangle. State Highway Number 62, 3½ miles of paved road, connects Chloride with this main route. In addition, numerous unsurfaced county roads lead to all the mining areas and to the various ranches. Roads to the ranches are kept in a good state of repair. Those to the mines are maintained only when the mines are being worked, and many are now impassable. The closest railroad connection is at Kingman, which is served by the main east-west Atchison, Topeka, and Santa Fe line.

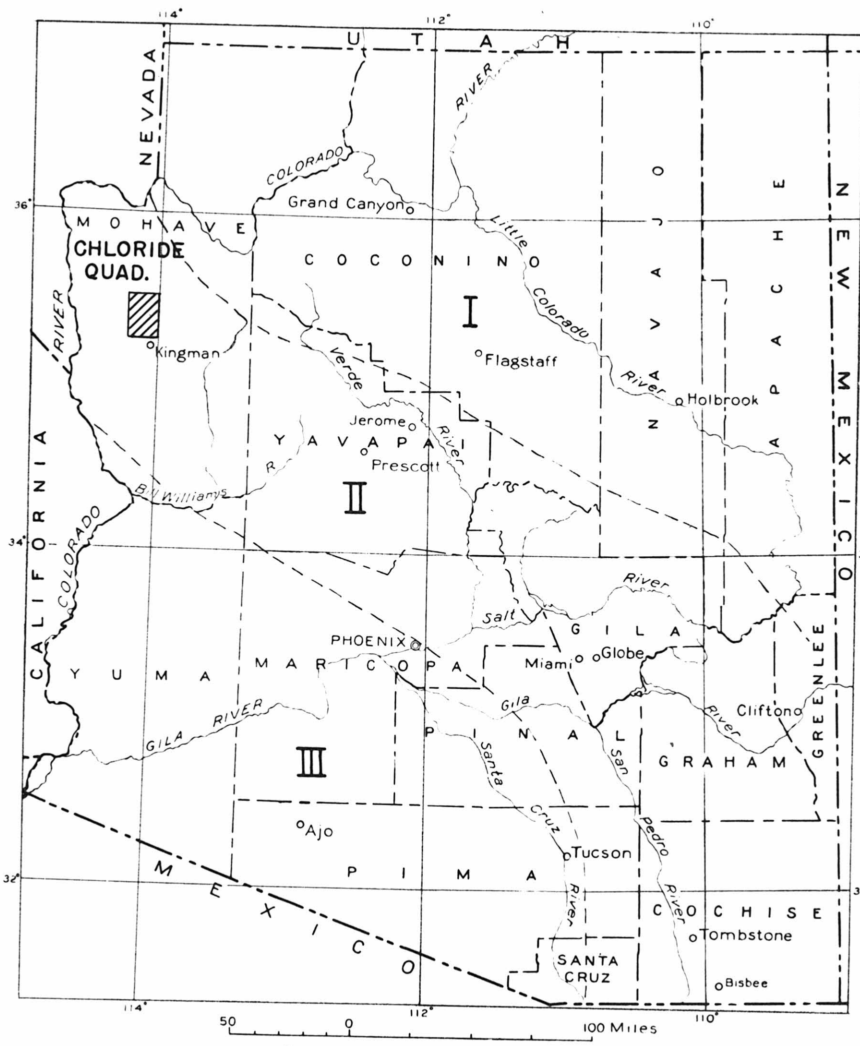


FIG 1—INDEX MAP OF ARIZONA.

Showing location of Chloride Quadrangle and Ransome's 1/ physiographic divisions of the state.

I -- Plateau Region
II -- Mountain Region
III -- Desert Region

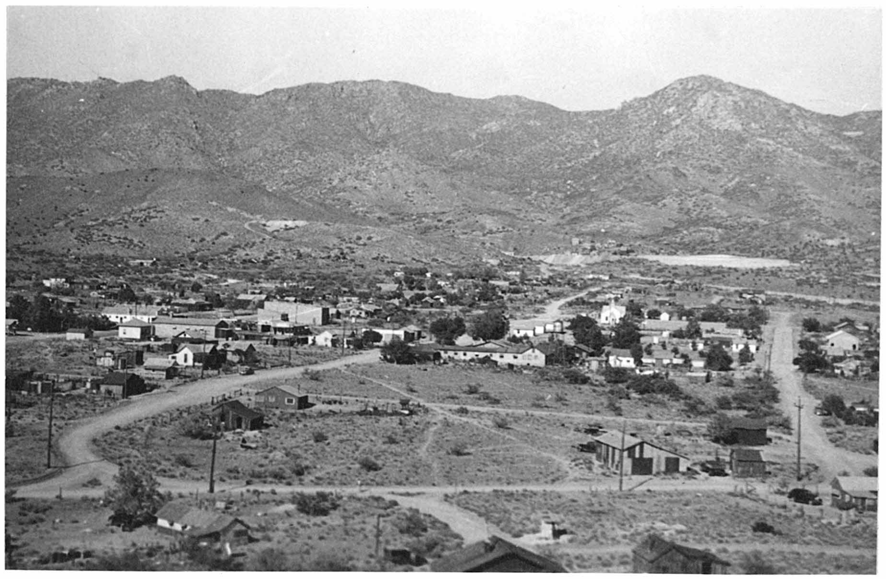


Figure 2 -- Chloride, Arizona . . 1948.
View looking east from Silver Hill.
Main ridge of Cerbat Mountains in
background.

PHYSICAL FEATURES

The Chloride quadrangle is within and close to the eastern border of the Basin and Range Province. It is part of the "mountain region" of Arizona, a northwest-southeast belt defined by Ransome 1/ as adjoining the Colorado Plateau region on the northeast and the "desert" region on the southwest (see Figure 1). The region displays the characteristic Basin and Range features of narrow mountain ranges separated by flat valleys.

The Cerbat Mountains occupy a central strip, covering approximately two-thirds of the quadrangle. They are a continuous range, starting immediately north of Kingman and continuing beyond the northern border of the quadrangle. The range trends north in the southern half of the quadrangle, veering to the northwest in the northern half. It varies from 6 to 10 miles in width within the quadrangle, the widest portion being in the north. The topography of the mountain mass is uniformly rugged and some of the slopes are precipitous. The highest feature is Cherum's Peak, near the center of the quadrangle, with an elevation of 6,978 feet. The lowest point has an elevation of 2,900 feet, in the extreme northeast corner of the quadrangle. This gives a total relief of 4,078 feet. The average relief, however, from the base of the mountains to the crestline is about 2,000 feet for the southern half of the range and 3,000 feet for the northern half.

The mountains are flanked on the east by the Hualpai Valley and on the west by the Sacramento Valley. Both these valley are alluvium covered basins with gentle gradients sloping away from the mountains. The Sacramento Valley, 8 to 10 miles wide, with drainage to the south, is bounded on the west by the Black Mountains, which run parallel to the Cerbat Range. The Colorado River flows along the west base of the

Black Mountains and is approximately 20 miles from the Cerbat Range. The Hualpai Valley, approximately 15 miles wide, is terminated on the east by the Cottonwood Cliffs and the Grand Wash Cliffs, impressive boundary scarps of the Colorado Plateau. Its flat surface is interrupted in its southern portion, between the Cerbat Mountains and the Cottonwood Cliffs, by numerous isolated hills, including the relatively low Peacock Mountains. Immediately north of this area, between the Cerbats and the Grand Wash Cliffs, the Hualpai Valley displays the expansive even surface of the Red Lake playa, which covers an area of almost 100 square miles.

The western side of the Cerbat Mountains presents a relatively uniform face, which rises abruptly from the flat skirt of the Sacramento Valley. Numerous canyons and washes, oriented more or less at right angles to the trend of the crest, break the continuity of the face, but a straight line of demarcation still exists between range and basin. On the east side no such line is visible. Instead a fingering of wide flat washes and mountain spurs occurs, with an abundance of isolated ridges and buttes extending out into the Hualpai Valley.

A flat pediment, as much as 1½ miles wide, is visible along the west base of the mountains. It is a comparatively even surface, cut without discrimination across all the rock types that compose the mountains, and it has the same general gradient as the surface of the Sacramento Valley. The pediment is veneered with a thin layer of alluvial material in most places, but recent dissection has removed enough of the veneer to reveal the continuity of the pediment surface. A similar pediment may exist along the eastern mountain base. A few small and scattered bedrock exposures, showing through the alluvial cover, seem to indicate a pediment. The presence of an extensive erosion surface cannot be proved, however.

The mountains are drained by canyons and washes, most of which open at right angles to the adjoining alluvial basins. There are no truly permanent streams, although short portions of watercourses may be induced to flow the year round by discharge from mine tunnels or from small springs. Normally, stream flow is maintained only by active rainfall. Run-off is short lived and that discharged into the valleys sinks rapidly into the alluvial fill.

Water for domestic use in Chloride is piped from the upper reaches of Samoa gulch. The volume is neither large nor constant, and the supply is augmented by wells and rain-water cisterns within the town. The storage of rain-water is desirable, as that obtained from springs, wells, or mines is extremely hard. Water in the other mining areas is obtained from wells, tunnels, shafts, and a few cisterns. The ranches have been able to develop water from small springs and wells within the mountain areas. Wells have been sunk in the alluvial fill of the valleys, but none is known to have encountered water.

The crystalline nature of the bedrock throughout the quadrangle precludes any appreciable primary porosity and permeability. Nevertheless, the well developed jointing normally assures a small but adequate supply of groundwater, both for human consumption and mill operation. However, following one or two years of sub-normal rainfall the water supply will become critically short.

Subsurface Water Level -- The level of the water table fluctuates from year to year, depending on the amount of rainfall the region receives. Schrader 2/ found the water level at a maximum depth of 400 feet and in some places "considerably nearer the surface" when he visited the area in the winter of 1906-1907. During the summer of 1941, following a winter of exceptionally heavy rainfall, the level was much higher. Shafts in the pediment areas along the base of the mountains were filled with water to within 5 or 10 feet of the collars. On the higher slopes the water levels in the shafts varied from 20 feet to as much as 60 or 70 feet below the surface. In 1947 and 1948, after two years of relatively dry weather, the level had dropped considerably. In the pediment areas water stood as low as 50 to 100 feet below the surface, while on the mountain ridges it was correspondingly lower.

CLIMATE AND VEGETATION

The quadrangle lies just inside the climatic zone that has been defined by R. J. Russell 3/ as "very hot summer desert". His modified Köppen symbols for such a region, "BWhh," signify that the mean January temperature is greater than 32 degrees F, and that the mean maximum temperature for at least three months is over 100 degrees F. This probably holds true for the bulk of the area, but on the higher mountain slopes it is likely that a cooler classification obtains. High temperatures prevail during summer days, but the low humidity and normally clear skies allow rapid cooling at night, and a diurnal temperature range of 50 to 60 degrees F. is not unusual. Temperatures are moderate to cool in the winter, with freezing conditions common at night.

There are no weather records available for the quadrangle, but the climatic data in Table I have been accumulated at Kingman.

Both temperature and rainfall vary with elevation. Conditions similar to those at Kingman, which has an elevation of 3335 feet, prevail along the base of the mountains and over the adjoining valley areas, where elevations vary between 3,200 and 3,800 feet. With increased altitude, temperatures are lower and average rainfall is increased. As can be seen in Table I, the rainfall is seasonal, occurring chiefly in the

TABLE I

Temperature and Rainfall at Kingman, Arizona

	25 Year Record - Degrees F			35 Year Record
	Extreme max	Extreme min	Mean Temp	Average Rainfall Inches
Jan	78	8	43.8	1.22
Feb	81	11	47.8	1.58
Mar	88	16	50.4	1.11
Apr	102	20	58.5	.58
May	106	30	65.2	.31
Jun	110	34	73.5	.16
Jul	110	35	78.6	1.01
Aug	117	43	80.5	1.53
Sep	107	31	73.7	.77
Oct	99	27	62.5	.70
Nov	89	13	53.3	.60
Dec	77	11	43.4	1.37
			Total Ave. Rainfall	10.94

Data compiled from Lausen 4/ and U.S. Dept. Agric. 5/

winter and summer months. Brief, convectional-current thunderstorms characterize the period from July to September. Very heavy showers may accompany these storms, but the rainfall is usually limited to a small area, as little as a few square miles in extent. Several such storms may be in progress at the same time, and rain-curtains falling simultaneously over isolated areas are not unusual sights during summer days. Rapid surface run-off follows these showers, and the washes may then be full to overflowing for a short time.

In the winter months, from December to March, when the hemispheric belt of cyclonic storms is shifted to the south, the area is subjected to occasional widespread rain. The fall received from these storms is typically much more gentle and persistent than that received in the summer showers, and the degree of surface run-off is correspondingly less.

Vegetation -- The lower portions of the region have a cover of short desert scrub. Creosote bush and several varieties of sage are abundant, including the bladder sage. The latter possesses numerous seed-filled, parchment-like pods which, when disturbed by a field boot, simulate an angry rattlesnake. Even to the initiated, a traverse through these shrubs is disturbing. Yucca is common, as are the prickly pear and cholla cacti. Barrel cactus occurs in a few places. Many varieties of desert grasses flourish in wet years. Even during dry periods, 1,000 to 2,000 head of cattle can be supported on the range within the quadrangle.

A thick stand of Joshua trees grows in the southwest corner of the quadrangle, and juniper trees occur on some of the pediment and alluvial areas near the mountains. Catsclaw (mimosa) and mesquite (prosopis) trees line most of the dry stream courses.

No definite line of demarcation exists, but on the higher slopes most of the desert scrub is replaced by a growth of pinyon pine, juniper, manzanita, and scrub oak trees. In places on the high ridges there is a dense cover similar to the California chaparral. Large cottonwood trees grow along the upper portions of some of the canyons.

FIELD WORK AND SCOPE OF REPORT

In the investigation of a mineralized area one of the principal aims is to determine factors of relationship between geology and ore deposition. Of particular interest, from both scientific and economic standpoints, are those factors which have exerted controlling influences in mineralization. A search for these factors of necessity entails a study of every phase of geology within a district, in as much detail as possible. However, perspective is also important. For example, a single mine may yield information which might appear conclusive as to the sequence of mineral deposition. Yet, when compared with data from other mines in the same area, this information may prove to be incomplete. Similarly, observations confined within the limits of a mining district can lead to erroneous general conclusions.

With the above in mind, the field work was conducted in two phases. The Chloride district was chosen for mapping which included the location and plotting of all the veins. (see Plate 1). The benefits of this choice lie in the fact that the Chloride district is the largest and most important of the mining areas and includes features of general geology, especially structure, that are absent in the other districts. This first phase of mapping was carried out in the summer of 1941. The base map used for the work was the advance edition of the U.S. Geological Survey's topographic map of the Chloride quadrangle, surveyed in 1939 and issued in 1941. This preliminary sheet has a scale of 1:48,000, or 1 inch to approximately three-quarters of a mile, with a contour interval of 25 feet. It was found to be accurate and highly satisfactory for this part of the work. A small area west of Chloride, not covered by the topographic sheet, was mapped through locations made by intersection, using Brunton compass sights on features within the quadrangle. In addition to surface mapping, all accessible underground workings in the district were studied, including both idle mines that could be entered and those few in active operation.

In the summers of 1947 and 1948, following an interruption occasioned by World War II, some additional time was spent in the Chloride district, and the second phase of mapping was conducted. With the purpose of gaining the necessary perspective, the areal geology of the balance of the mineralized belt was mapped and also a section along the east side of the Cerbat Mountains. (see Plate 3). Much of the mapping on the east side of the mountains was of reconnaissance nature, which satisfactorily furnished the regional information desired. The U.S. Geological Survey's final topographic sheet of the quadrangle, issued in 1944, was used as a base map. This has a scale of 1:62,500, or about 1 inch to a mile, and a contour interval of 50 feet. Although detailed mapping in the rest of the mineral belt was not feasible, comparative collections were made of the rocks and ores, and data were taken on as many mines and veins as possible.

In the course of mapping, four distinct types of mineralization were found. The principal one is base-metal ore in an extensive pattern of veins extending from the Chloride district on the north to the Cerbat district on the south. It is with this base-metal mineralization that the present report is primarily concerned. Though details are largely restricted to the Chloride area, discussion of general features is applicable to the entire zone.

A "porphyry copper" type of mineralization occurs in the Mineral Park district, coincident in location with a portion of the base-metal belt. Enough data were obtained to warrant brief discussion of the "porphyry copper" mineralization in this report. Full justice could only be done with more thorough study. Though to date no commercial deposits have been discovered, the area of mineralization is large and offers a problem for detailed investigation.

Other types of mineralization, which can be discussed only summarily, include a unique copper-silicate deposit in late gravels and turquoise deposits in the Mineral Park area.

In addition to containing a variety of ore deposits, the Cerbat Mountains are strategically located a scant 15 miles from the edge of the Colorado Plateau. They are approximately 35 miles due south of the Virgin Mountains, in Nevada, which also face the plateau. As stated by Longwell in his report on the Muddy and Virgin Mountains 6/

"the location of the region near the boundary between the Basin Ranges and the plateau province gives it a critical interest, because the stratigraphy, structural, and physiographic relations of basin to plateau must be determined largely by a study of this border zone."

The Chloride quadrangle, in comparison with the Virgin and Muddy Mountains and the plateau, exhibits both features of similarity and of marked difference. Much of the data that have regional bearing unfortunately falls in a class of geologic omission rather than presence. However, it is hoped that the coverage afforded the physical and historical geology in this report will add an increment to the understanding and interpretation of these broad problems.

PREVIOUS WORK

Probably the first geologist to visit this general area was Jules Marcou. He crossed the region in February 1854 as a member of the Whipple survey 7/. Marcou named the Cerbat Mountains but applied the term to all the ranges between the plateau country and the Colorado River, and even beyond. His scant, though accurate, observations are summarized in a geological map and section prepared from his notes by W. P. Blake.

J. S. Newberry traversed the region and made some brief observations on the Cerbat Range mineral deposits, during his work with the Ives expedition in 1857-58 8/.

A party from the Wheeler survey 9/ visited the region in the fall of 1871 and made a brief report on the veins and activities of the

"Hualapais" district. A second Wheeler party, under the direction of Oscar Loew 10/, examined the district in 1875. In addition to a description of mining activity, Loew gives an accurate list of the ore minerals.

The first comprehensive geologic reconnaissance to include the Chloride quadrangle was made by W. T. Lee in 1903 and 1904 11/. His discussion includes the rock types, topography, and structure of the Cerbat Mountains and the adjoining valleys. A few specimens of igneous rocks from the area were determined by Albert Johannsen.

The only thorough reconnaissance of the mining districts was made by F. C. Schrader in 1906-1907 12/. His observations and conclusions regarding the general geology and ore deposits are excellent, and his report still serves as a "bible", not only for the Cerbat region, but for the bulk of the mining areas in Mohave County. Schrader's report has been the chief source for most of the few short summaries that have been written subsequently. His descriptions of the principal mining properties are valuable for their detailed record of early history, development, and production. Microscopic determinations on the rocks and ores were made by Waldemar Lindgren and B. S. Butler.

R. M. Hernon has made the most complete recent summary 13/. His report is brief and adds little to the general descriptions and conclusions previously drawn by Schrader.

E. S. Bastin studied some of the rich silver ores from the standpoint of secondary enrichment 14/. His conclusions concerning the paragenesis of the silver minerals are valuable, as those minerals are now extremely scarce in the ore deposits.

Short papers have appeared in various mining publications from time to time, but they have been restricted to technical mining features or short geological descriptions of single mines and prospects.

GEOLOGY

GENERAL OUTLINE

The Cerbat Range is composed essentially of massive crystalline rocks, the bulk of which are pre-Cambrian in age. The oldest rocks are quartzite, mica schist, hornblende-diopside schist, and amphibolite. Younger, and more abundant, are granite gneiss and granite. Much of the rock is orthogneiss, but perhaps an equal amount represents granitization of the older schists. Lit-par-lit migmatites are numerous, and minor amounts of gabbroic and dioritic rocks also are associated with the granitic bodies. Pegmatite, aplite, and diabase dikes are widespread. The original rocks were disposed in an orogenic fold system, but igneous invasion and granitization have left only remnants of the folds. Localized intense shearing produced mylonites, which are scattered throughout the basement complex.

The area is devoid of Paleozoic rocks and probably of Mesozoic rocks. Intrusions of granite porphyry in the Chloride and Mineral Park districts resume the geologic record. These are classed as Tertiary in this report. They were accompanied by the injection of numerous granite porphyry dikes and were followed by minor amounts of pegmatite and aplite and abundant lamprophyre dikes.

Small areas of volcanic rocks exist along the flanks of the range. The rocks consist of a lowermost andesitic series, a middle rhyolitic series, and a topmost andesite flow, all presumably of Tertiary age. Thin sheets of Quaternary olivine basalt cap the sequence along the west side of the range. This basalt also lies on and interfingers with alluvial deposits. Numerous large and small rhyolite dikes and a few andesite and basalt dikes occur within the basement rocks.

Several periods of faulting and erosion are indicated by the volcanic rocks. The latest faulting is of basin-range type and has outlined and caused the elevation of the present mountains. The greatest vertical displacement has been on the west side, and the Cerbat Range is essentially an eastward-tilted fault block, in part modified into a horst. This mountain making is believed to have occurred in late Tertiary and Quaternary time. It was accompanied by the accumulation of large quantities of detritus in the adjoining basins. Recent vertical displacement is postulated from terraces within the canyons and the dissected nature of the pediment at the west base of the range.

Sulfide mineralization seems to have occurred after the close of the Tertiary volcanic period. The first phase consisted of "porphyry copper" mineralization in a highly shattered portion of the granite porphyry stock in the Mineral Park district. This was succeeded by the profuse formation of strong fissure veins, which carry the base metal ores that have made the exploitable deposits of the region.

A late fault cuts the gravels west of the Mineral Park district. This has been mineralized, along with the immediately surrounding alluvium, and forms the Emerald Isle copper deposit.

DETAILED DISCUSSIONS OF THE ROCKS

CERBAT COMPLEX

Distribution and Relation to Other Formations -- A basement assemblage of metamorphic and igneous rocks, for which the term Cerbat Complex is proposed, forms approximately 90 percent of that portion of the Cerbat Range included in the Chloride quadrangle. Granite gneiss, of both metamorphic and igneous origin, is the most abundant rock type. It contains discontinuous layers of crystalline schists, small dioritic and gabbroic bodies, highly porphyritic granites, and pegmatite, aplite, and diabase dikes.

The complex is capped along the extreme eastern and southern borders of the range by isolated Tertiary volcanic rocks, most of which have been preserved in down-dropped fault segments. Along the western edge of the Chloride district most of the basement is terminated by the Sacramento fault, (see Plates 1 and 3) which has also preserved Tertiary volcanics on its down-dropped side. In the Chloride and Mineral Park districts the complex has been intruded by granite porphyry of Tertiary(?) age. Numerous young silicic and mafic dikes, along with a host of veins, have likewise invaded these basement rocks.

METAMORPHIC ROCKS

Vertical to steeply dipping layers of hornblende-diopside schist and amphibolite, biotite schist, quartzite and lit-par-lit gneiss comprise the oldest group of rocks in the region. They may be encountered anywhere in the Cerbat complex. They typically occur together but in no particular or consistent sequence. Exposures, though numerous, are discontinuous, and more abundant granite gneiss surrounds, interleaves, and grades into the schists. However, in several places enough of these layered rocks have been preserved to reveal their disposition in fragments of large folds. These folds, and evidence of original bedding in the quartzites, suggest that the layered rocks were originally a series of stratified deposits. No estimate of the initial thickness of the series can be made, but the sum of individual layers in the limbs of a large anticline in the Chloride district suggests that it would be measured in thousands of feet.

In addition to the lit-par-lit rocks, many of the associated gneisses are believed to be migmatites.

Superimposed on all the major rock types of the Cerbat complex are narrow zones of mylonite, which were formed by localized intense shearing.

QUARTZITE

Distribution -- Outcrops of quartzite are scattered and rare. Discontinuous layers 2 to 3 inches thick occur in the north end of Silver Hill, in the wash north of the Empire mine, and northeast of the Towne vein. A bed 2 to 3 feet thick is exposed along the north slope of the ridge just north of Merit Spring. One notable occurrence is a steeply dipping layer 40 to 50 feet thick, which is included in a series of pegmatite and hornblende schist layers lying adjacent to the northern boundary of the Ithaca Peak porphyry intrusion of the Chloride District. An excellent outcrop of this bed is exposed in the northeast corner of S28, T24N, R18W, just north of the intrusive contact. In all places the quartzite is associated conformably with layers of hornblende schist. It has no distinctive topographic expression.

Petrography and Origin -- The rock is characteristically light gray, weathering to a moderate brown. It is finely laminated and can be split into thin plates, along very fine-grained dark layers which contain concentrations of biotite. The texture is interpreted as being blasto-psammitic, on the basis of apparent relict sub-angular to sub-rounded grains. Discrete grains as much as 0.5 millimeter in diameter are visible in hand specimen.

In a thin section made from the quartzite that occurs in the north end of Silver Hill, what seem to be original quartz grain boundaries, outlined by tiny specks of darker minerals, can be seen in ordinary light. Under crossed nicols much of the original grain arrangement is not visible. Recrystallization has occurred, resulting in the formation of irregular grains and bands of quartz. Most of the bands are elongated parallel to the layering of the rock. The quartz interlocks in an intricate pattern and is characterized by the presence of strain shadows. In negligible quantity, and averaging 0.1 millimeter in size, are dark brown grains of biotite, wisps of muscovite, irregular grains of magnetite, sericitized grains of andesine feldspar, and stringers of pale chlorite. Tiny needles of apatite are common in much of the quartz.

Microscopic examination of the rock from the outcrop north of Merit Spring reveals similar features, except that it contains approximately 15 percent andesine, as anhedral grains 0.1 to 0.8 millimeter in size, interlocked with the quartz. Biotite is also more abundant, making up about 1 percent of the rock. Strain shadows in the quartz are largely absent.

The quartzite is significant because it indicates that the oldest series of rocks in the Cerbat Complex is, in part, sedimentary in origin. Though some removal and addition of material may have taken place during recrystallization, the almost wholly siliceous composition, and the apparently relict fine bedding and blastopsammitic textures, are reliable signs of an original layered, fine-grained, quartz sandstone. 15/

BIOTITE SCHIST

Distribution -- Biotite schist is widely scattered throughout the Cerbat Complex. It occurs both as narrow septa in lit-par-lit gneiss, and as layers forming separate rock units.

The discrete strata of biotite schist are generally only a few inches to a few feet thick, and are commonly interleaved with hornblende-diopside schist and fine-grained granite gneiss. In some places biotite schist seems to be gradational with the hornblende-diopside rocks. The occurrence of small pegmatite or quartz stringers in the schist is not unusual. The widest exposure seen is a 15 to 20 foot-thick layer in the ridge due east of Mayswell Peak. The well-developed schistosity of the always steeply-dipping or vertical strata promotes thorough weathering, and the schist is typically soft and friable.

Petrography and Origin -- The schist is dark gray to black where fresh and moderate brown where weathered. Textures are lepidoblastic with porphyroblastic phases. A specimen from the outcrop east of Mayswell Peak gives a typical picture under the microscope. It is a gnarled, porphyroblastic type, containing 50 percent biotite. The biotite occurs as plates in the groundmass, averaging 0.25 to 1.5 millimeters in diameter, with parallel to decussate orientation. It is fresh and strongly pleochroic from dark brown and greenish brown to light yellow. Inclusions, which are scant, are sphene, feldspar, magnetite, and apatite.

The balance of the groundmass, making up 35 percent of the rock, consists largely of feldspar and quartz. Approximately one-half of this is oligoclase (An_{20}), one-quarter orthoclase, and one-quarter quartz. These minerals occur as clear grains, which are roughly equant to slightly elongated, 0.4 to 0.6 millimeter in average diameter, and contain poikiloblastic inclusions of sphene, apatite, and biotite. Magnetite is the most abundant of the minor minerals. It occurs as euhedral grains as much as 1.2 millimeters long, and as dust and specks along cleavage lines in the biotite. Some grains are partly altered to hematite. Sphene and apatite have formed fairly numerous idioblastic crystals as much as 0.5 millimeter long, which are included in the other minerals.

The porphyroblasts, which compose 15 percent of the rock, are mostly oligoclase, but some are orthoclase, and microcline. They form "eyes" up to 5 millimeters in diameter, which are xenoblastic to roughly rectangular in shape, have highly irregular borders, and are intergrown with the adjoining minerals. The feldspars are uniformly clear, with unoriented small and large inclusions of the groundmass minerals, notably biotite. Only one crystal shows spots of alteration to sericite. The nature of the inclusions, as pointed out by Goodspeed 16/, plus the clarity, and stages of growth represented by small and xenoblastic, to larger, roughly idioblastic crystals, are indicative of true porphyroblasts and not relict grains or phenocrysts.

The original nature of the schist cannot be determined conclusively. The rock occurs in a crystalline schist series derived partly from sediments on the one hand and partly from what are believed to have been mafic igneous rocks (now hornblende-diopside schists) on the other. The general composition of the biotite schist is such that it may represent either sediments or igneous rocks. 17/ Furthermore, the present composition very likely is partly a result of subtractions and additions of material during metamorphism. The layers are narrow and unversally in intrusive igneous surroundings, and a certain amount of metasomatism would be expected. However, it is believed that the biotite schist probably represents former argillaceous sediments which were interbedded with thin sandstones and mafic volcanic rocks.

HORNBLENDE-DIOPSIDE SCHIST AND AMPHIBOLITE

Distribution and Surface Expression -- Somber-hued layers of hornblende-diopside schist make up the bulk of the crystalline schist series and occur throughout the Cerbat Complex. They vary from a few inches in width to layers over 400 feet across and in places are several miles long. Thick representative layers are abundant in the lower slopes of the Chloride district.

The rock is resistant to weathering and erosion and tends to develop distinct low ridges and tabular outcrops. A good example of the latter can be seen east of the Johnny Bull claim, where low "gravestones" jut out from the hillside. One large mass of schist, along the east side of Tennessee Wash, has formed a black butte that rises 350 feet above the wash and serves as a landmark that is visible for many miles (see Figure 3).

Petrography and Origin -- In fresh specimens the schist ranges from grayish black or greenish black to medium gray. A speckled or banded appearance is common, from an alternation of light and dark minerals. The schist characteristically weathers to a moderate or light brown. Most specimens are fine-grained with varying degrees of acicular schistosity, but patches of the rock are massive, either fine or coarse grained, and are best termed amphibolites. Many exposures contain narrow stringers of pegmatite, which are disposed in small folds (see Figure 4) or in crenulated and contorted ptygmatic patterns. Presumably all of the schists

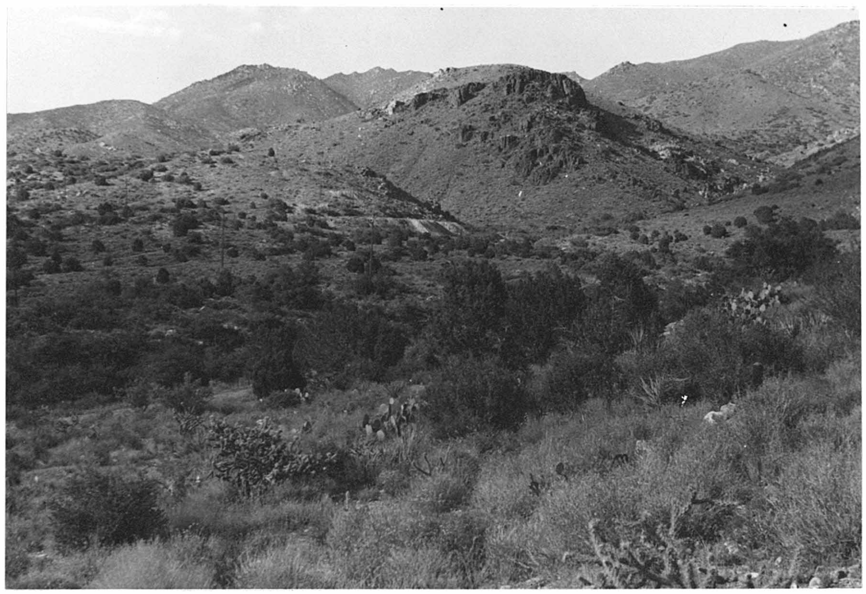


Figure 3 -- View north along Tennessee Wash, showing large mass of hornblende schist. Dump of Schenectady mine in center of picture.

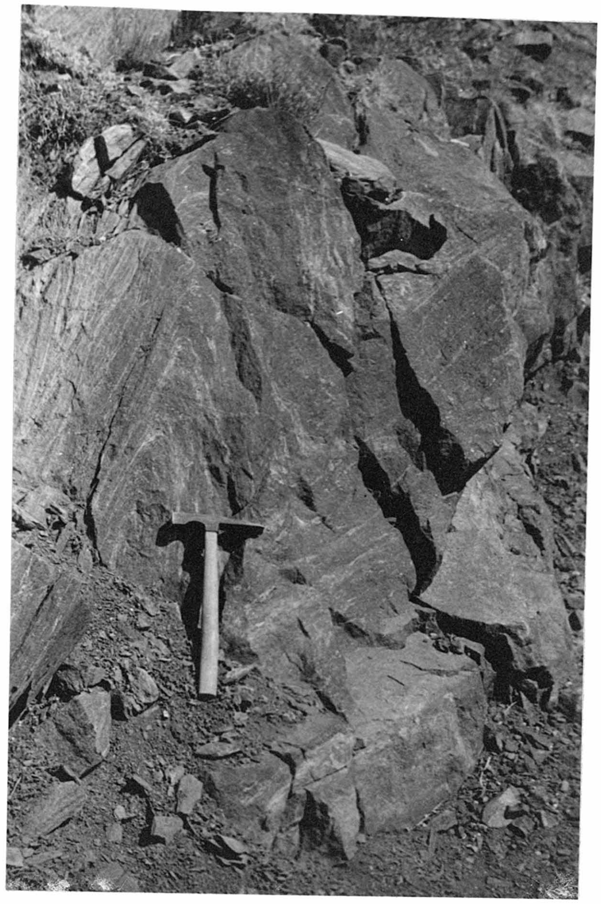


Figure 4 -- Small folds in hornblende schist. Road-cut along crest of range, approximately 1/4 mile southeast of Summit mine.

have been intricately folded, but the effects are not revealed by the apparently simple linear schistosity.

Under the microscope, the rocks are seen to consist essentially of brown and green varieties of hornblende, calcic plagioclase, diopside, and hypersthene. All gradations exist, from facies containing only hornblende and plagioclase to those with only diopside and plagioclase. The compositional varieties and their gradational relationships are shown in Table 2, which was prepared with data from 11 thin-sections.

TABLE 2

Mineral Composition of Hornblende-Diopside Schist and Amphibolite Suite. Figures in Percent.

Hornblende (Color)	Feldspar (% An)	Diopside	Hypersthene	Biotite	Remarks
80 Green	20 (75)				Amphibolite
75 "	25 --				
55 Brown	45 (55)				
50 "	50 (60)			Present	
20 Green	80 (70)			Present	
60 Brown	35 (50)	5			
35 "	35 (45)	30			
20 "	35 (60)	Present	45	Present	
20 Green	10 (62)	55		12	3% Sphene
	50 (62)	45		5	
70 Brown		10	15	5	Amphibolite

The two colors of hornblende are mutually exclusive in any one specimen. Both have strong pleochroism where unaltered. In the brown type X = pale yellow, Y = light brown, and Z = light greenish brown. In the green type

X = clear yellow, Y = bluish or brownish green, and Z = blue green. The average composition of the feldspar is An_{60}, with a range from An_{75} to An_{45}. The diopside is colorless, has weak dispersion, and $Z \wedge C$ = 35 to 40 degrees. The hypersthene, in both observed instances, has only weak pleochroism, in which X = reddish yellow, Y = pale yellow, and Z = pale green. Minor minerals are magnetite, apatite, sphene, and biotite, though the latter, as shown in Table 2, can occur in moderate proportions.

The average grain size is 0.5 millimeter or less; however, poikiloblastic crystals of hornblende, diopside, or hypersthene occur as plates measuring as much as 5 by 10 millimeters, giving a distinct porphyroblastic texture. Inasmuch as the series ranges from schist to amphibolite, the textures include everything from nematoblastic to granoblastic patterns. Tension cracks, perpendicular to the schistosity, are abundant in the nematoblastic varieties.

Specimens commonly show little alteration. Secondary products formed from hornblende, however, include chlorite, magnetite, biotite, and epidote, whereas fibrous uralite (actinolite), chlorite, and magnetite were observed as products of diopside. Secondary products after feldspar are sericite, calcite, epidote, zoisite, and clay mineral. Hematite and limonite have formed from magnetite.

The rocks that contain contorted stringers of pegmatite are similar to those that do not. The only observable difference, aside from the veinlets, is the presence of isolated grains of quartz, orthoclase, and microcline in the usual assemblage of hornblende, plagioclase, and pyroxene. The veinlets themselves, which are characteristically a few millimeters wide, are also composed of quartz, orthoclase, and microcline. In the thin section examined, quartz is most abundant (90 percent), with orthoclase and microcline about equally divided. Much of the feldspar is microperthitic, and the quartz contains numerous strings of tiny inclusions. The grains have an average diameter of 0.6 millimeter and are irregularly intergrown, both with themselves and with included and bordering hornblende and plagioclase. Most of the grains show faint undulatory extinction.

It is possible for rocks of this general nature to be derived from chloritic, calcareous sediments 18/, but the common source of hornblende schists and amphibolites is mafic igneous rock 19/. Buddington has described amphibolites with the same mineral assemblage (labradorite, diopside, hypersthene, hornblende) derived from gabbros in the Adirondack complex of northeastern United States 20/. In the Cerbat complex the hornblende schists occur in narrow, tabular bodies, which undeniably are elements of folds. Therefore, the original rocks are believed to have been basaltic flows or tuffs. It is conceivable, of course, that some or all of them may have been sill-like intrusions in an original series of sediments. An extrusive origin, however, is in accord with that attributed by Campbell and Maxson to similar amphibolites that occur in the Grand Canyon, which display relict pillow structures 21/.

GRAPHITE SCHIST

Schrader mentions a graphite schist, occurring between Mineral Park and Stockton Hill 22/, and a specimen of graphite schist was donated by Mr. Lyon Kay, of Mineral Park, who stated that it had come from the east side of the Cerbat Range. The graphite, though rare, is an indication of the presence of carbonaceous material in the original rocks of the Cerbat complex.

The specimen received from Mr. Kay is dark silvery gray, with a well developed lepidoblastic texture. Microscopically it is seen to contain 35 to 40 percent graphite, which occurs as abundant microscopic inclusions and as ragged lamellar crystals as much as 0.2 by 0.8 millimeter in section. The crystals are oriented in a schistose, slightly crenulated pattern. The balance of the rock consists of about 25 percent orthoclase feldspar, 25 percent cordierite (?) and 10 percent quartz. All three of these minerals are irregular in shape though elongated, average 0.3 by 0.5 millimeter in size, and are highly poikiloblastic with graphite inclusions. Some of the orthoclase is microperthitic. Minor minerals are apatite and sphene. The rock has been selectively altered, for the orthoclase is clear and fresh, whereas much of the cordierite has changed to pinite (?). Stringers of limonite occur along some of the cleavage planes in the rock.

MIGMATITE

Lit-par-lit Gneiss Phase

Distribution -- Lit-par-lit gneiss, like the crystalline schists, is distributed throughout the Cerbat complex. Outcrops showing distinctive streaked patterns vary in width from a few feet to more than 50 feet. The bodies are tabular and may extend longitudinally for hundreds of feet but are discontinuous and typically have indistinct contacts. All are steeply dipping to vertical in attitude. The rock is ordinarily resistant and may form bold outcrops that stand as much as 10 to 15 feet above the surrounding country.

Petrography and Origin -- The gneiss is medium gray in general hue, and weathers to a moderate brown. It has been formed by the injection of sheets of aplitic and pegmatitic granite into bodies of biotite and hornblende schist, producing an alternation of dark and light bands. (see Figures 5 to 8).

The dark bands are composed in part of the minerals previously described as present in the schists, namely biotite, orthoclase, microcline, oligoclase, and quartz for the biotite schists and hornblende, biotite and calcic plagioclase for the hornblende schists. The minor minerals magnetite, sphene, and apatite are also present, but no pyroxene was observed in the specimens examined. The presence of biotite in the hornblende schists that are now part of a lit-par-lit rock is probably essential, for a completely acicular schist would not be susceptible to sheet injection. In addition to the above minerals, pink almandite (?) garnet is commonly present. In one specimen, from an outcrop just east of the Tennessee mine staffhouse, an emerald green garnet (uvarovite?) occurs, as well as almandite. The specimen is further distinctive in that it contains about 3 percent sillimanite. The sillimanite is present principally as the variety fibrolite, in elongate masses of interlacing needles, intergrown with biotite, garnet, quartz, and feldspar. Small patches of fibrolite were observed in other specimens, but on the whole the mineral is rare. Varying quantities of the invading granitic material are interspersed with the other minerals in the dark bands.

The light bands typically contain 50 percent or more of quartz, and varying amount of orthoclase, microcline, and sodic plagioclase. Mafic minerals are completely lacking in the central portions of the wider bands. Undulatory extinction in quartz and curving twin lamellae in feldspar are common, and many specimens show some crushing and granulation of the larger grains. Much of the feldspar is microperthitic. Some of the bands are fine grained and aplitic in texture, and some are pegmatitic. Graphic intergrowths of quartz and feldspar occur in places.

Both light and dark bands vary in width from a fraction of a millimeter to more than ten centimeters. The light bands in places pinch and swell irregularly, and the dark bands follow their configuration

Figure 5 -- Lit-par-lit gneiss, just west of road to Clay ranch, and 3/4 mile due north of Arizona Magma mine.

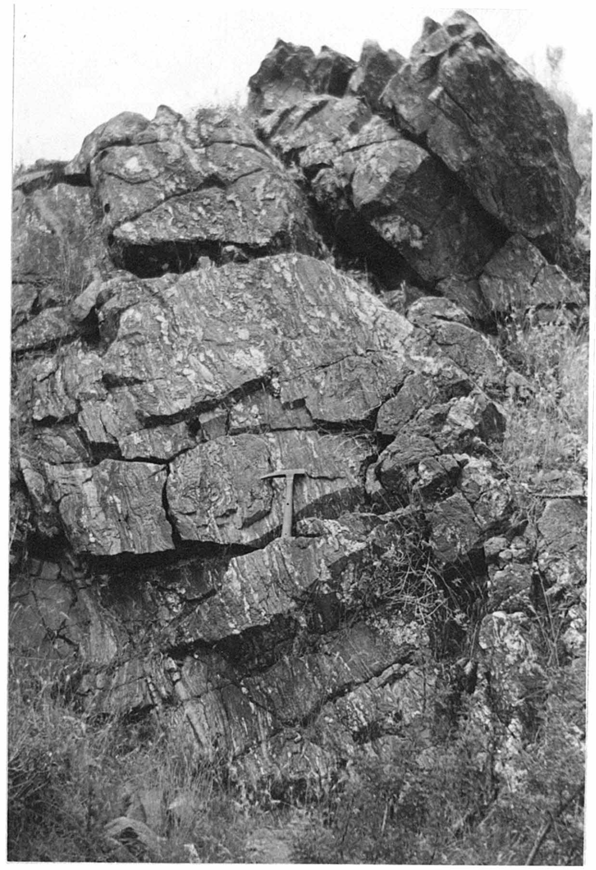


Figure 6 -- Lit-par-lit gneiss. Same locality as Figure 5.

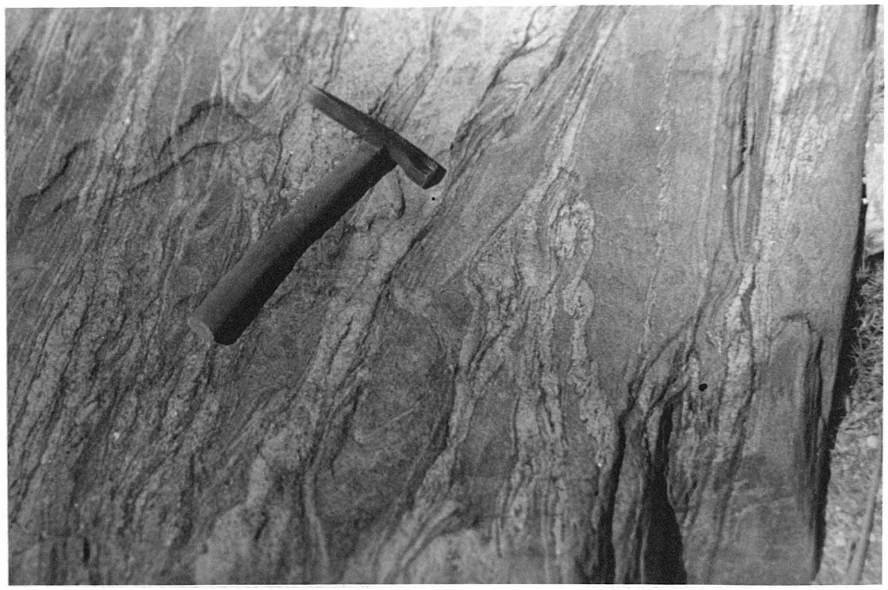


Figure 7 -- Lit-par-lit gneiss in north side of Cerbat Canyon. T 22 N, R 17 W, west center section 8.

Figure 8 -- Lit-par-lit gneiss. Same locality as Figure 7.

(see Figure 7). Some dark bands are interrupted or fade out in places but continue after an interval. This feature of discontinuity is present both microscopically and in field relations. The contacts of many bands appear sharp in hand specimen, though the border minerals always interlock, whereas some contacts are hazy and indistinct. All degrees of transition exist between bands of aplite or pegmatite and schist, and thorough mixing has produced many narrow layers that cannot be distinguished from the granite gneiss that forms the bulk of the Cerbat complex. The field boundaries of the exposures of lit-par-lit gneiss are of similar transitional nature.

Ptygmatic folds are always present in the pegmatite and aplite sheets. These folds show the usual characters of extreme contortion, lack of correspondence in form with the fabric of the enclosing schist, lack of competence, and absence of correlation between forms assumed by different layers in a single outcrop or specimen. Difference in form is well demonstrated where a contorted layer exists adjacent to rèlatively straight, undeformed sheets. There seems to be a uniform trend to the axial planes of the folds, roughly parallel to the foliation of the host rock.

The foliation of the lit-par-lit gneiss is, in all observed exposubes, conformable with the structural grain of the region. Nothing was seen to indicate that the attitude of the invaded schists had been disturbed.

All the above features are strikingly similar to those described by Fenner for pre-Cambrian injection gneisses in northwestern New Jersey 23/. Fenner's analysis of the mode of origin of these gneisses is believed to apply equally well in the Chloride quadrangle. This modè is one of active invasion by a highly fluid silicic magma. The magma entered among the layers of a foliated rock in a quiet manner, causing no violent disturbance of the attitude of the folia. The host rock was impregnated and somewhat softened by an "advance dilute portion" of the magma, which facilitated the injection process and initiated transformation of much of the invaded material.

Other Composite Gneiss Phases -- A detailed consideration of the possibility that much of the gneiss, both granitic and mafic, may be migmatitic instead of magmatic in origin will not be attempted. In the lit-par-lit gneisses all degrees of transition from schist bands to granite gneiss occur. The classification of the latter as a composite rock, formed by processes of metasomatism and magmatic injection, is valid, at least for the areas where such gradational relationships exist. Whether extrapolation may be applied, and a similar mode of origin assumed for gneisses that look the same but lack exposures showing gradation, is largely a matter of opinion. It is believed that a large amount of the gneiss, perhaps 50 percent or more, is migmatite, whereas the balance represent "normal" magma.

In support of this view is evidence that there are at least two distinct ages of gneiss. For example, along the crest of the range in the Summit mine area, thin septa and lenses of fine-grained gray gneiss, which are transitional with layers of hornblende schist, are surrounded and cut by a later medium-grained gneiss. The sharp transgressional boundaries of the latter are taken to indicate that it is an igneous or orthogneiss, whereas the former is apparently a migmatite derived from hornblende schist. Repetitions of these relationships occur throughout the range.

A suggestion that migmatite is present in large amount is presented by the numerous areas where granite gneiss is transitional with layers of schist and lit-par-lit gneiss. This is illustrated in the high mountain slopes east of Chloride, where granite gneiss composes at least 90 percent of the rocks yet rarely continues for more than a few hundred feet without grading into discontinuous septa of biotite and hornblende schist or patches of lit-par-lit gneiss.

The presence of ptygmatic folding in areas of granite gneiss is thought to indicate migmatization. This feature is well exposed in a road cut along the crest of the range in the east center of section 5, T22N, R17W. As shown in Figure 9, highly contorted pegmatite veinlets exist in what otherwise appears to be a simple granite gneiss. The walls of the veinlets are distinct, but the border minerals interlock with the minerals of the gneiss. The axial planes of the folds are roughly parallel with the foliation of the rock.

An argument which could be used to uphold widespread migmatization is that throughout the Cerbat complex the foliation in the gneisses is conformable with the textural and structural grain of associated schists. Undoubtedly some of this foliation has been inherited from previous schists. However, emplacement of intrusive rocks has been influenced by pre-existing structure and any flow-banding should be conformable to this structure. Furthermore, uniform directional stress apparently existed prior to, during, and after intrusion of most of the igneous rocks in the complex, and foliation produced by it would likewise parallel the regional trend. Granitization, in the sense that it is synonymous with migmatization 24/, has seemingly been of considerable importance in the formation of a large portion of the Cerbat complex. However, even with extremely detailed study, precise resolution of areas of granitization and areas of purely igneous gneiss would be difficult, if not impossible.

MYLONITE

Distribution -- "In view of the often complex tectonic operations with which regional metamorphism is closely connected, it cannot be supposed that shearing stress merely suffers, like temperature, a steady decline. Rather must we expect incidental revivals of more or less intense shearing stress, recurring, it may be, at various stages of the

Figure 9 -- Ptygmatic folding of pegmatite veinlet in granite gneiss. Road cut east center section 5, T 22 N, R 17 W.

continued fall of temperature".

The above generalization by Harker 25/ is well borne out in the Cerbat complex, where effects of continued stress are visible in the microstructures of both metamorphic and igneous rocks. Intense, local shearing is evidenced by zones of mylonitic rocks, which were observed at many widely scattered points in the complex. Examples are exposed just southwest of the Arizona Magma dump, in the Boulder Dam claim, at the Towne mine, south of Mullen ranch, and in the saddle of the ridge in the extreme southeastern portion of the quadrangle. In all places the mylonite has a northeast trend, parallel with the general structural grain. The zones vary from a few feet to 10 or 12 feet in width. They have no distinct borders but pass gradually into the surrounding gneissose or schistose rocks.

Petrography -- In hand specimen the mylonites are greenish gray to dark gray and appear much like a porphyroblastic slate or phyllite. They are either massive, or finely laminated. In some places slickensided surfaces exist. Augen of feldspar are commonly present, ranging in size from barely visible specks to lenticular crystals over an inch long. The larger grains were observed where pegmatite veinlets seemed to be part of the parent rock.

Under the microscope the effects of intense shearing and crushing are reflected in dark laminae which are composed of mineral aggregates so fine-grained that they are sometimes not resolvable under highest magnification. Where identification is possible, the minerals are seen to be principally sericite and chlorite, with some epidote, quartz, and feldspar (probably albite). Interleaved with the dark bands are aggregates, lenticles, and stringers of quartz, typically inter-crystallized with small grains of orthoclase. Sinuous, pinching and swelling bands of quartz, with uniform optical orientation over distances as great as 2 millimeters indicate flowage and recrystallization. Augen of microperthitic orthoclase are numerous and augen of microcline occur in some specimens. The average length of the crystals is 1 to 2 millimeters. They are typically ellipsoidal and are enclosed and wrapped by the finely granular bands. The interiors may be strongly fractured, and the borders are always crushed and granulated. In addition to microperthite, myrmekite and inclusions of biotite and oligoclase were noted in some of the augen. All the augen seem to be relict grains of previous rocks and are affected by cataclasis but not by recrystallization. Other relict minerals observed are tiny grains of almandite garnet, scattered sparsely along one or two laminae of a specimen, occasional flakes of biotite, and a few crystals of sphene. These are anomalous minerals, as they are high-grade metamorphic products, existing in rocks which have suffered extreme cataclasis with accompanying recrystallization to the low-grade mineral assemblage sericite-chlorite-epidote. On the basis of their retrogressive metamorphic character, the rocks may appropriately be classed as phyllonites (phyllite mylonites).

Age -- The localized intense shearing and the resultant zones of mylonite are assigned to the pre-Cambrian. This is based essentially on the negative evidence that wide mylonite zones were observed to occur only in the areas of the Cerbat complex. Inasmuch as a gap in the geologic record, involving probably all of the Paleozoic and Mesozoic, exists in the area, this is a tenuous assignment, but the best that can be made.

CONDITIONS OF METAMORPHISM

The metamorphic rocks of the Cerbat complex have evolved through the action of several metamorphic processes. The chief causes have been orogenic forces and plutonic igneous intrusion.

The first major phase of metamorphism was produced by orogenesis, with strong directed pressure and probably much heat of geothermal and mechanical origin. Originally layered rocks were squeezed into large folds and recrystallized to form a series of crystalline schists. These dynamothermal effects encompass and extend beyond the area studied and the action may be termed "regional" metamorphism. The essential characteristics of the crystalline schists are believed to stem from these early effects.

A second phase of intensive metamorphism was imposed through igneous intrusion, which appears to have followed closely or to have been concomitant with the last stages of orogenesis. The intrusion was characterized by injection phenomena and the production of migmatite. The metamorphism attributable to it is classed as "plutonic". Following Turner's definition, this means essentially deep-seated regional metamorphism, at high temperatures and pressures, accompanied by deformation and characterized by metasomatism, infiltration, and injection phenomena derived from igneous intrusion 26/.

Using the concept of metamorphic facies 27/, the grade of metamorphism that evolved under these combined dynamothermal and plutonic conditions can be determined. The hornblende-diopside schists and amphibolites provide the critical sensitive mineral assemblage needed to indicate the grade. A broad classification can be made on the basis of the occurrence together of hornblende and calcic plagioclase. This amphibolite facies embraces both medium and high-grade regional metamorphism and corresponds in general to the sillimanite, kyanite, staurolite, and, in part, the garnet zones of the Scottish Highlands 28/. A more precise definition is given by the occurrence together of plagioclase-hornblende-diopside-hypersthene, which is indicative of high-grade regional metamorphism 29/. This assemblage represents a special high-grade subfacies which not only can be assigned to the amphibolite facies, but which has characteristics of the granulite facies. It is analogous with a mineral assemblage in the Archean rocks of the Adirondack complex, where intense regional metamorphism has been accompanied and aided by injection of granitic batholiths 30/. It also corresponds to the sillimanite zone of regional metamorphism. In connection with this, the previously described lit-par-lit gneiss that contains the assemblage sillimanite-almandite-orthoclase is noteworthy.

No conclusions can be drawn as to the evolution of the migmatites. Mechanical injection of pegmatitic and aplitic material is indicated in the lit-par-lit forms, and magmatic soaking and impregnation of the host rocks probably preceded and accompanied injection. The source of the pegmatite and aplite is obscure. They may have been of igneous origin, but their production by differential fusion (anatexis) is perhaps more likely, because the pegmatite and aplite sheets cannot be correlated definitely as differentiates of any adjacent large intrusion. The anomalous appearance of pegmatite and aplite, as the first plutonic products in the Cerbat complex, is more easily explained as a function of differential fusion than of late differentiation of a hidden batholith, considering the presumably great depth of erosion of Archean terrains.

Deformation appears to have continued from the early phases of metamorphism, through the plutonic stages, and even to have outlasted the crystallization of the igneous rocks, thereby resulting in retrograde metamorphism. The existence of continued stress during the injection of magma is suggested by the ptygmatic folding in the migmatites. There is correspondence between the outlines of the folded igneous layers and the trend of schistosity in the host rock, which implies injection under conditions of active deformation, and signifies that orogenic folding was not yet complete at the time of first magmatic intrusion.

Retrograde Metamorphism -- In regionally metamorphosed rocks retrogressive changes may be brought about by declining temperatures and by variations in stress, producing both mineralogical and structural modifications. Both types of change have affected the metamorphic rocks of the Cerbat complex, but the effects of stress far outweigh those of temperature.

Ignoring near-surface changes due to weathering and restricted alteration caused by hydrothermal sulfide mineralization, only a few mineralogical changes can be attributed solely to declining temperature at depth. These include small amounts of chlorite developed from garnet and biotite, amphibole from diopside, biotite from hornblende, distinct crystals of zoisite and epidote from plagioclase (rather than hydrothermally produced obscure grains in saussurite), possibly some sericite from potash feldspar, and much microperthite in orthoclase and microcline. The exsolution of albite is the most common mineral change.

Structural changes are much more in evidence. Continuation and perhaps intensification of shearing stress during the gradual decline of temperature, has left its widespread mark. Characteristic features are fractures and displacements in garnet, pyroxene, and hornblende, granulation and crushing of the component grains in the rocks, especially quartz and feldspar, undulatory extinction and deformation of twin lamellae, the presence of sheared "augen" in many gneisses, and extreme comminution, stretching, and milling in the mylonites. The mylonites are the best examples of well-developed retrogressive metamorphism, for in them intense deformation has been accompanied by mineralogical reconstitution from a high-grade assemblage to one containing the low-grade minerals chlorite, epidote, sericite, and albite.

INTRUSIVE IGNEOUS ROCKS

GRANITE GNEISS

All the granite gneiss in the region is discussed under this heading. It should be kept in mind, however, that granitization or migmatization is believed to have been widespread, and that many of these rocks may actually be composite in origin.

Distribution and Surface Expression -- Granite gneiss is the principal constituent of the Cerbat complex and accordingly is the most abundant and widely distributed rock type. It forms massive rugged surfaces, with individual erosional shapes tending toward spheroids or ellipsoids. Where jointing is strong, sheer-walled blocks and columnar crags have developed.

Petrography -- The rocks are characterized by diverse texture and structure but relatively uniform composition. Exposures exist that have no obvious gneissic banding, but these are in the minority. The majority show every range from faintly banded types to flaser gneisses with well-developed "augen" of feldspar. Aside from phenocrysts (or porphyroblasts or porphyroclasts, as the case may be) which reach more than 3 centimeters in length, the rocks are predominantly fine grained (grains less than 3 millimeters). The granularity is rarely uniform, different degrees of porphyritic texture being the rule. Most specimens are light to medium gray when fresh, but some are pinkish gray and others light bluish gray. The weathered surfaces are ordinarily light brown to moderate yellowish brown. Segregations of biotite as much as 6 millimeters in diameter give a speckled appearance to many specimens.

Under the microscope, the diversity of texture and structure is even more marked. Most of the gneiss has been cataclastically deformed, and the component minerals are surrounded by a microcrystalline mosaic of crushed grains. However, some specimens have strong gneissic banding but show no crushing or granulation. In the cataclastically deformed rocks undulatory extinction and curved twin lamellae complement the "mortar" structure. Recrystallization of the crushed material is ordinarily not advanced, but in some specimens myrmekite seems to have developed under the influence of stress, and granulated quartz shows solution and recrystallization to an interlocking pattern.

The principal mineral is orthoclase, which occurs in quantities of 50 to 70 percent. In large grains it is characteristically poikilitic (or poikiloblastic), with inclusions of one or more of the minerals quartz, albite, biotite, apatite, and oligoclase. In most specimens microcline is present in proportions of 10 to 15 percent. Both these potash feldspars are typically microperthitic. Oligoclase (average An_{25}) accounts for 5 to 10 percent and quartz 10 to 20 percent of the rocks. The only characterizing mafic mineral which appears consistently is biotite. This occurs as fresh, dark brown to greenish brown flakes, in quantities averaging 4 percent. In not uncommon association with the biotite, and producing strong pleochroic halos in it, are crystals of allanite. A few grains to a few percent of green hornblende, and some sodic andesine, were observed in some darker colored granite gneisses. Transitional borders with nearby bodies of schist point to a migmatitic origin for some of these varieties.

Minor accessory minerals are scattered grains of apatite, sphene, magnetite, and zircon. Secondary minerals are negligible. Those observed are chlorite and magnetite formed from biotite, sericite from orthoclase and microcline, and sericite and calcite from oligoclase.

Origin -- It has been emphasized, in the discussion of migmatite, and at the head of this section, that the gneisses may be of either composite or igneous origin. If the belief that the two types are present in about equal proportions is reasonable, their widespread occurrence indicates that the igneous members represent an intrusion of batholithic proportions, which has engulfed, assimilated, displaced, and migmatized large quantities of schist.

The gneissic structures are of complex derivation. Some of the foliation has been inherited from schists, some probably represent flowage controlled by structures of the intruded rocks, and some may be due to crystallization under directional stress. Superimposed on these is cataclastic deformation, which has emphasized the foliation at times, and which in places may have been the sole responsible agent. This later shearing, while localized in intensity, was parallel with the already established structural trend and did not produce any noticeable discordant features.

MAFIC GNEISSES

Mafic varieties of gneiss are included under the category of igneous rocks with less assurance than in the case of the granite gneisses. No large exposures occur, but examples are abundant throughout the areas of the granite gneisses. The chances are that most of these small isolated bodies are composite rocks. On the other hand, some might be mafic segregations of magma. Several distinctly tabular bodies could represent either migmatized schists or intrusive sills.

Petrography -- The rocks are medium to dark gray and weather to a moderate brown. They are fine to medium-grained, may be granular massive, but usually show faint if not strong gneissic banding. Tonalite and quartz-gabbro were determined under the microscope.

<u>Quartz-gabbro variety</u> (Rankin Tunnel dump) -- This rock has a porphyritic, hypidiomorphic granular texture, with an average grain size of 1½ millimeters. Labradorite (An_{62}) makes up about 60 percent of the rock. The labradorite occurs in two sizes, one as saussuritized phenocrysts (?) 2 to 5 millimeters long, and the other as fresh grains, 1 to 2 millimeters long, in the groundmass. The smaller grains are partly sericitized but otherwise unaltered. The only additional felsic constituent is clear quartz, in the proportion of 5 percent, which occurs as anhedral, interstitial grains about 0.5 millimeter in size.

Biotite, highly pleochroic from dark greenish brown to light yellowish brown, and brownish green hornblende are present in quantities of approximately 15 percent each, in grain sizes of 1 to 2 millimeters. Similar sized crystals of pale green augite ($Z \wedge C$ = 52 degrees) compose about 5 percent of the rock. Much of the augite is altered to fibrous uralite and chlorite. Magnetite is present, especially on the ends and along the cleavages of the biotite. Numerous tiny crystals of apatite and a few grains of zircon occur as accessories.

The anomalous quartz has apparently been derived from a pod of granite pegmatite, which occupies one corner of the specimen.

<u>Tonalite variety</u> (New Moon mine area) -- The texture in this specimen is hypidiomorphic granular, porphyritic, with distinct though crude gneissic structure. Phenocrysts (?) 1.5 to 5.0 millimeters long, mostly of sodic andesine (An_{33}), but some of quartz and orthoclase, make up about 60 percent of the rock. The other 40 percent is groundmass, with grains about 0.6 millimeter in average size. Of these, andesine makes up 55 percent, orthoclase 5 percent, quartz 10 percent, biotite 25 percent, and hypersthene 5 percent, with a few scattered grains of microcline. The orthoclase and microcline are partly microperthitic and in places have growths of myrmekite. Much of the quartz has undulatory

extinction, but there are no crush structures. The most abundant minor accessory is magnetite. Apatite needles are numerous, and sphene occurs sparingly. Zircon is included in some of the biotite.

Secondary products are minor but include sericite and kaolin after the feldspars, magnetite and chlorite after biotite and hypersthene, and some bastite after hypersthene.

DIANA GRANITE

The Diana granite is a unit of the Cerbat complex. It is a coarsely porphyritic intrusion, which was mapped separately in the Chloride district. Other porphyritic granites occur elsewhere, notably along the east side of the range. They are similar in general appearance and might be mapped as correlatives if detailed work were applied to the entire quadrangle. The name Diana grantie is proposed, after the Diana (Arizona Magma) mine which occurs approximately in the center of the mapped area.

Distribution and Surface Expression -- The area occupied by this coarsely porphyritic body is in the central part of the western half of the Chloride district. It is roughly circular, with a diameter of about 1-3/4 miles. In an east-west direction it extends from Silver Hill to a point one-eighth of a mile from the western boundary of the quadrangle. To the north it is sharply defined against schists and fine-grained gneiss half a mile south of Clay ranch. To the south it is capped by alluvium and disappears just beyond State Highway 62.

The medium to coarse-grained texture of the rock makes it particularly susceptible to weathering and erosion. This, together with the fact that it is located along the base of the mountain range, has contributed substantially to the development of a pediment. The effect has been so marked that the pediment reflects the distribution of the rock, forming a reentrant into the mountains which outlines the dimensions of the body. (See Figure 10) The surface is essentially flat, sloping gently to the southwest, and it blends insensibly with the overlapping alluvium. The pediment is subject to interruptions only where isolated septa or pendants of more resistant older schist and gneiss occur. A few more resistant portions of the Diana granite have yielded spheroidal boulders, but these are infrequent.

Relations to Other Rocks -- The emplacement of the Diana granite was a function of the distribution of the crystalline schists, for the granite fills the core of a large northeast-pitching anticline and is virtually surrounded by steeply dipping layers of schist, gneiss, and pegmatite. Broadly, and many places in detail, its contacts with the schist and older gneiss are distinct. However, in places interaction and apparent assimilation have taken place, producing narrow zones of composite rocks. In some border schists, intimate sheet-injection was observed that seemed to stem from the Diana granite.

One thick septum or pendant of schist and gneiss, $1\frac{1}{2}$ miles long and three-sixteenths of a mile wide, occurs in the eastern portion of the intrusion and forms a distinctive ridge in the otherwise uniform surface. Other discontinuous bodies of older rock are scattered through the granite, but the largest of these is only 200 by 800 feet at the surface.

The Diana granite is cut by moderate amounts of pegmatite and has served as host for numerous younger mafic and silicic dikes. Along part of its western border it is in fault contact with a series of Tertiary extrusive volcanic rocks.

Petrography -- The rock is medium gray on fresh fracture and weathers to a light or moderate brown. Many of the outcrops show weak foliation, and some exposures are highly gneissic or mylonitic. The texture is

Figure 10 -- Flat pediment surface developed on Diana granite. Calico Peak in background. Arizona Magma mine left center. View looking north.

porphyritic, with a medium-grained groundmass.

Tabular, slightly embayed orthoclase phenocrysts make up about 20 percent of the rock. Most of these phenocrysts are 1 to 2 centimeters long, but some measure as much as 5 centimeters. The orthoclase is poikilitic, containing small inclusions of chloritized biotite and minor amounts of tiny quartz blebs. The phenocrysts are typically microperthitic, with hair-like stringers of albite.

The average grain size in the groundmass is 2 millimeters. Forty persent of the groundmass consists of orthoclase, which is microperthitic. Some slight alteration to sericite and kaolin has taken place in the orthoclase, and small patches of myrmekite occur on the borders of some crystals. Microcline accounts for 30 percent of the groundmass, while clear quartz makes up 15 percent. Under crossed nicols some of the quartz displays strong undulatory extinction, and a cataclastic "mortar structure" is present in some specimens. Ten percent of the groundmass is composed of oligoclase (An_{25}). An early generation of oligoclase, which crystallized prior to orthoclase, is thoroughly saussuritized, whereas crystals that formed at about the same time as the orthoclase are comparatively fresh. The rest of the groundmass is composed of wisps and shreds of dark brown biotite. Much of the biotite has altered to green chlorite, with the release of abundant granules of magnetite. Apatite, sphene, and zircon occur as additional accessories.

Origin and Age -- Various features suggest a plutonic igneous origin for the Diana granite. Its relative purity, contrasted with the heterogeneous and thoroughly mixed areas of schist and older granite gneiss, is one feature. Its control by pre-existing structure, with limitation to the core of an anticline, is another. Perhaps the most indicative is its igneous texture, particularly the large phenocrysts. These, though poikilitic, do not contain wholesale inclusions of all the other minerals, such as occur in the poikiloblastic "sieve" pattern so characteristic of metamorphic rocks.

The strongly gneissic phases are not abundant and seem to have formed in response to the same localized post-consolidation shearing stresses that were imposed on the rest of the Cerbat complex. Mylonites in the Diana granite have the same northeast trend as those elsewhere. Gneissic structures at and parallel to the borders of the intrusion are classed as flow banding.

The age of emplacement of the Diana granite seems to be later than the formation of much of the Cerbat granite gneiss on the basis of its discordant relations with bands of granite gneiss that are interleaved with schists. Its inclusion in the pre-Cambrian, with the other members of the Cerbat complex, is warranted, so far as direct evidence goes, only by the lack of any better determination.

PEGMATITE

Distribution -- In addition to the pegmatite layers that are part of the migmatites, dikes of all sizes are numerous in the Cerbat complex. These range up to masses as much as 600 feet wide and a mile or more long, and their distinctive outcrops are often discernible from a distance of several miles. Large white pegmatite bodies are particularly well displayed in the limbs of the large anticline in the Chloride district. Here they have been injected as sill-like masses between layers of dark schist and stand out in a sharp contrast of color. The pattern in Calico Peak is a good example of this (See Figure 11). In addition to dikes or sills, some pegmatites are in the form of irregular lenses and pockets. Pegmatite is common in the walls of the quartz-sulfide veins.

Petrography -- The pegmatites are of simple granitic composition.

Gray to milky quartz composes 30 to 40 percent of the rock, with the remainder made up of orthoclase and minor amounts of light bluish gray microcline. Microperthite is well developed in the feldspars. Small amounts of sericite and kaolin are present as alteration products. A wide range of granularity is present, with some crystals as much as 4 or 5 inches in size. Many of the bodies, however, are uniform in texture. Graphic intergrowths of quartz and feldspar are numerous. Many dikes display effects of shearing stress which is shown by undulatory extinction and microscopic granulation in thin-section and by megascopic elongation and foliation.

Departures from the prevailingly simple composition were noted in only a few pegmatites. In a specimen from the area just east of the Alice claim all the feldspar is oligoclase, which is strongly antiperthitic with stringers and patches of orthoclase. A dike northwest of the Dorothy prospect contains a small amount of black tourmaline (schorlite) in a graphic intergrowth with gray quartz. Muscovite was observed in several dikes, but on the whole it is rare. Tiny rutile crystals occur in some of the muscovite. A small quantity of beryl was found in pegmatite on the claim at the south end of the Jim Kane group 31/. At the open pit mine of the Consolidated Feldspar Corporation, on the southeast slope of Bull Mountain, large masses of quartz and orthoclase contain small seams and segregations of biotite and rough prismatic crystals, a few inches long, of black vitreous-appearing gadolinite. Detailed study of this deposit might reveal the presence of other rare minerals.

Origin and Age -- At least two ages of pegmatite are present in the Cerbat complex. The earlier occurs as sheets and veinlets in the lit-par-lit gneisses. It is interpreted as the oldest intrusive rock of the complex and is possibly a product of differential fusion (anatexis).

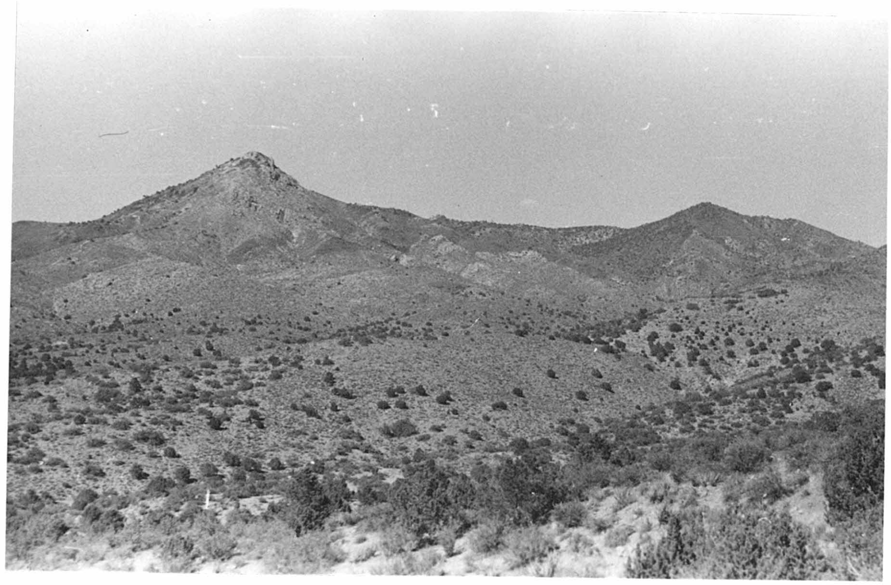


Figure 11 -- South face of Calico Peak. White pegmatite interleaved with dark schist bands, in north limb of large anticline.

Many of the larger intrusions of pegmatite may also be of this age.

A later age is attributed to pegmatites that cut the Diana granite and similar porphyritic granite bodies in the complex. Their post-Diana age suggests an origin as late products of magmatic differentiation. The dikes that contain tourmaline, muscovite, beryl, and gadolinite, which require volatile "mineralizers" in their formation, probably belong to this later group. Other dikes, lacking such minerals, and which cannot be correlated with the Diana granite, may belong to either age as far as composition and appearance are concerned.

The interpretation of the pre-Cambrian pegmatites is complicated by the fact that some of the dikes in the complex are probably of post-Cambrian age, for the later Ithaca Peak granite porphyry intrusion was followed by pegmatites that are similar to the simple granitic types discussed above.

APLITE

Aplitic phases occur in the pegmatites, and isolated small aplite dikes occur in some places. The preceding section on origin and age of the pegmatites is equally applicable to the aplites.

Petrography -- Textures are allotriomorphic granular, with an average grain size of 1 millimeter. Crushed, microgranular borders are present around the grains in some specimens. The composition is similar to that of the simple pegmatites except that microcline and orthoclase are more abundant, and quartz is less abundant. Furthermore, many small dikes carry 1 to 2 percent of almandite (?) garnet, occurring as dodecahedra, scattered uniformly through the rock. Some of the garnets contain small inclusions of quartz, and many are partly altered to chlorite.

DIABASE DIKES

Distribution -- Fine to medium-grained diabase dikes cut all the other rock types of the Cerbat complex. The dikes vary in width from a few feet to as much as 150 feet, and some can be traced for more than a mile. Excellent examples can be seen at the Hercules and Midnight mines and in the area just north of the Arizona Magma mine. Vertical to steeply dipping attitudes are typical, but three dikes that cut the ridge east of the Mary Bell mine strike N 40 to 50 degrees W and dip at angles of only 15 to 40 degrees E. Diabase occurs in one or both walls of many of the quartz-sulfide veins.

Petrography -- Fresh specimens are dark gray, and the weathered forms are light brownish gray to moderate brown. Most of the dikes have been thoroughly altered either by weathering or by hydrothermal action, but the rock is easily identified in a hand specimen by its diabasic texture. The dikes range in granularity from very fine-grained chilled border facies to coarse-grained examples in which the average length of the feldspar laths exceeds 3 millimeters.

An exceptionally fresh specimen, from a dike in the north side of Cerbat Canyon, was examined in thin section. Approximately 65 percent of this diabase consists of labradorite (An_{60}), in the form of euhedral laths 0.2 to 0.3 millimeter wide and 1 to 2 millimeters long. Anhedral grains of pigeonite ($2V$ = 10 to 20 degrees, variable; $Z \wedge C$ = 38 degrees), in proportions of 25 to 30 percent, are interstitial with the feldspar laths. The pigeonite grains are as much as 3.5 millimeters in size. Associated with the pigeonite is 1 or 2 percent of hypersthene, as anhedral grains averaging 1 millimeter in size. Magnetite occurs to the extent of about 5 percent, filling interstices and replacing the feldspar and pyroxenes. Some of the magnetite crystals measure as much as 2 millimeters in diameter. Irregular flakes of biotite are scattered through the rock, in close association with magnetite in most places. Apatite is abundant as tiny grains and needles included in the feldspar.

Secondary products in this specimen are minor. A few grains of labradorite are partly altered to a saussuritic mixture of calcite, epidote, zoisite, albite, and chlorite, the hypersthene is partly altered to bastite, and some of the pigeonite has been partly replaced by pyrite, biotite, green chlorite, and calcite. Pyrite also has replaced parts of some hypersthene and magnetite grains.

In many specimens the feldspar laths are both sericitized and saussuritized, and the interstitial mafic minerals are completely altered to fibrous green hornblende, chlorite, calcite, and epidote.

In several places the diabase dikes invaded fracture lines previously occupied by pre-Cambrian pegmatites. Appreciable digestion of the pegmatite took place and the result was the formation of a pink-tinted hybrid rock. Clumps of partially consumed pegmatite, grading into the general mixture, serve to identify the mode of formation.

Age -- Diabase was not observed to intrude any rocks other than those of the Cerbat complex. On the basis of this relationship it is assigned to the pre-Cambrian. However, as the youngest intrusive rock of that group, it could be of almost any age. It possibly came in at the same time as the diabases of the Grand Canyon, in which event it would be Algonkian in age 32/.

ARCHEAN HISTORY OF THE CERBAT COMPLEX

The Archean history of the Cerbat complex can be divided into four broad stages:

(1) The first decipherable event in the region was extensive volcanism, with the accumulation of probably thousands of feet of basaltic

rocks. At intervals throughout this period quartz sandstones and shales were deposited, possibly grading in places into volcanic material. The amount of these sediments seems to have been small, but granitization and igneous intrusion have masked a large volume of the older rocks, much of which was perhaps sedimentary.

(2) An intense orogenic disturbance (Arizonan revolution 33/) followed the accumulation of the volcanic and sedimentary strata. The beds were folded and subjected to high-grade regional metamorphism, with horizontal compression imposing a uniform northeast structural trend on the region. Probably near the end of the orogeny pegmatitic granite magma or magmatic solutions invaded the deformed rocks. Lit-par-lit injection took place on a large scale, and all the rocks seem to have become soft and plastic, for ptygmatic folding was widespread. Much migmatization of the schists occurred, obscuring parts or all of many folds. However, the resulting granite - gneiss migmatite inherited the structural grain of the schists, and the foliation is, in general, conformable to the regional trend. In places the foliation clearly follows the course of plunging folds. Fundamentally unchanged directional stress continued through and beyond this stage.

(3) Intrusion of granitic magma, possibly batholithic in scale, followed this preliminary "soaking" and sheet injection phase. The emplacement of the granite bodies was influenced by the structure of the schists, and much primary gneissic banding, parallel to the guiding schist layers, is believed to exist. What process was most important in the intrusion of the magma is not known. Some displacement of the pre-existing rocks probably took place, and stoping is suggested by the occurrence of xenoliths. Assimilation products are well developed at the contacts of bodies such as the Diana granite. Whatever the process,

the result has been the obliteration of continuous folds, of which only scattered remnants now remain. The introduction of large quantities of pegmatite, with auxiliary aplite, marks the close of this intrusive stage.

Continuation or revival of stress, with unchanged orientation, impressed secondary foliation or heightened primary gneissic structure in the bulk of the igneous intrusions. Localized intense shearing, after consolidation of the plutonic bodies, formed narrow zones of mylonite throughout the Cerbat complex.

(4) The final event was deep erosion and peneplanation to a surface of virtually no relief. This may have taken place in late Archean time. However, the portions of the surface that are preserved lie beneath Tertiary volcanic strata, and erosion during intervening ages could have formed or perfected this surface.

The diabase dikes of the Cerbat complex are not accounted for in the above history. They are believed to be much later, though possibly still pre-Cambrian (Algonkian) in age.

AGE AND CORRELATION OF CERBAT COMPLEX

The complete lack of fossiliferous rocks in the Cerbat range precludes any conclusive age determinations, and the Cerbat complex is placed in the Archean on the basis of its petrologic similarity to other Archean terrains. "Archean characteristics" that it possesses are a high-grade of regional and plutonic metamorphism, extensive injection of magmatic material under conditions of general softening and plasticity, and the dominance of true granite in the intrusive members.

The most logical and accurate correlation to be made is with the Archean rocks of the Grand Canyon, which possess lithological, structural, and historical features similar to those of the Cerbat complex. Campbell and Maxson 34/ have described four periods in the Archean history of the Grand Canyon: (1) deposition of thick, monotonous sedimentary formations, dominantly sandy clays with quartz sands; (2) eruption of basalts, with intercalated thin sediments; (3) orogeny and granitic intrusion; and (4) erosion. With the exception of the lack of thick sediments (which may have been granitized) in the Cerbat complex, this sequence of events and the resulting assemblage of quartzites, mica schists, hornblende schists, amphibolites, many migmatites, and large volumes of granite and pegmatite, are almost identical in the two regions. Application of orogenic forces was likewise the same, resulting in a northeast structural trend. Campbell and Maxson suggested restricting the name Vishnu series to the meta-sediments, and in that sense it has no correlative in the Cerbat complex. In the broader sense, as used by Noble 35/, however, the Vishnu schist can be correlated with the Cerbat schists.

Lithologically and structurally the Cerbat complex is similar to the Archean rocks in the core of the Virgin Range, Nevada, briefly described by Longwell 36/. With other areas correlation is weak and can be based only on the northeast structural trend. In Wilson's summary of the pre-Cambrian of Arizona basin ranges 37/, this general northeast grain is seen to be characteristic wherever the early pre-Cambrian has been described in Arizona, including the Pinal and Yavapai schists of the south and central areas.

ITHACA PEAK PORPHYRY

Distribution and Topographic Expression -- Two intrusions of granite porphyry, within the Cerbat complex but presumably much younger, are exposed along the western flank of the range, one in the Chloride district and the other in the Mineral Park district. They are similar in texture and composition and are assumed to be the same age. Both are designated Ithaca Peak porphyry, after the imposing crag of that name in the Mineral Park district.

The intrusion in the Chloride district is in the form of a curved, steeply-dipping sill from 2,000 to 5,000 feet thick. The arc-like outcrop forms the northern boundary of the western half of the district. The eastern limb of the arc rises from alluvium just south of the town of Chloride, and underlies the pediment on which the town is built. The outcrop extends north of Chloride 1½ miles, thence curves to the west and southwest, ending against the Sacramento fault and Tertiary volcanic strata just beyond the western border of the quadrangle. The maximum inside chord of the arc is 2½ miles. North of Chloride the granite porphyry has been eroded into a group of rugged ridges and peaks that rise to heights of 1,000 feet above the town. The remainder of the arc, to the west, consists essentially of one main ridge that is much less rugged and which, aside from isolated peaks, decreases gradually in elevation from east to west.

The intrusion in the Mineral Park district is apparently a roughly equidimensional stock, 3½ to 4 miles in diameter, with its center approximately at Gross ranch. The word "apparently" is used here, as the intrusion is flanked on the west by alluvium and continues an unknown distance beneath the surface of the Sacramento Valley. Several thick tongues extend out from its southeast side, the largest reaching a mile and a half through Union Basin to the Golconda mine. A gently rolling pediment, with exposed widths up to a mile, has been developed along the western side. The portion of the stock within the mountains has been eroded into a cluster of steep rugged peaks with an average relief of about 700 feet. These stand out in sharp contrast to the surrounding areas of the grayish Cerbat complex, as they have weathered to light brown and reddish brown, and also have rougher slopes (See Figures 12 and 13). Most of the rough slopes and crags are due to silicification of the rock.

In addition to this large sill and stock, numerous thin dikes or sills and a few small plugs of granite porphyry have invaded the Cerbat complex. Dikes are especially abundant in the Chloride district.

Petrography -- Fresh specimens are a light gray. Surface exposures weather to light brown or pale reddish brown and in parts of the Mineral Park stock to dark reds and browns. A large portion of the stock has been mineralized, and the oxidation of pyrite accounts for much of the reddish color.

Parts of both intrusions are foliated, and some border facies are strongly gneissic. Foliation is better developed, however, in the Chloride district sill than in the Mineral Park stock.

The texture of the rock is hypidiomorphic porphyritic, with a fine-grained to microcrystalline groundmass. Microcrystalline, interlocking grains of quartz and feldspar compose 10 to 15 percent of the rock. Phenocrysts of orthoclase, in quantities up to 50 percent, average 3 millimeters in size, and in exceptional cases phenocrysts reach 2 centimeters. Of the fine-grained minerals, which average 0.5 millimeter in size, orthoclase accounts for about 50 percent. Many of the grains are microperthitic. A small amount of microcline, some microperthitic, is present in most specimens, while oligoclase occurs in proportions of 3 to 6 percent. Clear quartz is abundant in the groundmass (about 40 percent) and phenocrysts up to 2 millimeters in size are not rare. The chief mafic mineral is biotite (5 to 10 percent), which occurs in irregularly resorbed brown to green plates. Small quantities of pale

Figure 12 -- Ithaca Peak, Mineral Park district. Note distinctive light color and rough, steep slopes. White scar at left is dump of turquoise workings. View looking southeast.

Figure 13 -- West face, Mineral Park portion of Cerbat Range. Cherum's Peak at left. Hills of Ithaca Peak porphyry in center.

green hornblende were observed in a few specimens.

Accessory minerals include magnetite, sphene, zircon, apatite, and, in some specimens, garnet. Alteration products, in unmineralized areas, consist of chlorite and magnetite after biotite and hornblende, and sericite and kaolin after feldspar.

Specimens with secondary foliation are characterized by varying degrees of crushing and granulation. Undulatory extinction characterizes the quartz grains, and some feldspar phenocrysts are stretched and sheared. In several places local intense shearing was observed in the Chloride intrusion. In one specimen a mylonitic layer one-quarter of an inch thick occurs in an otherwise only faintly foliated rock.

In a plug approximately 250 feet in diameter, at the head of Cerbat Canyon, a finer-grained phase has developed, evidently under conditions of more rapid cooling. This rock is light gray where fresh, weathering to a grayish brown. Phenocrysts of orthoclase make up 20 percent of the total composition. These are $1\frac{1}{2}$ by 3 millimeters in average section, partly microperthitic, poikilitic with quartz, biotite, and apatite, and some show Carlsbad twinning. The crystals are invariably rounded and resorbed. The balance of the rock consists of an extremely fine-grained to cryptocrystalline groundmass. Quartz, orthoclase (average 0.06 millimeter) and biotite (average 0.05 by 0.1 millimeter), with fairly abundant specks of magnetite and a few crystals of apatite, account for three-quarters of the groundmass. The remainder is cryptocrystalline material, interstitial with the identifiable grains. Both phenocrysts and grains in the groundmass are oriented in a planar flow pattern.

Origin and Intrusive Relations -- The microcrystalline phase of the groundmass in the Ithaca Peak porphyry suggests that it is a relatively shallow, hypabyssal intrusive. This is its chief distinguishing characteristic, in comparison to the plutonic rocks of the Cerbat complex, for in composition and even in gneissic structure it is highly similar to much of the pre-Cambrian granite.

The body in the Chloride district was intruded concordantly into curved layers of Archean schist and gneiss, and its exposure serves to emphasize the banded nature of the outcrops that surround a central core of Diana granite. It can be classed best as a curved sill that was injected in a near-vertical attitude into a steeply-pitching large anticline.

The Mineral Park stock was likewise influenced by pre-existing structure, though not to the same degree. Its northwestern edge follows a steeply-pitching anticline, and anticlinal septa of Archean rocks are present in the northern portion of the stock. The configuration of its southern border, and the attitudes in the adjacent Cerbat complex, suggest that it has also followed an anticline there. In many places, however, its contacts are parallel to the foliation of the adjacent country rock but do not follow distinct folds. In a few places it is strongly discordant with neighboring structure.

The contacts of the intrusions are sharp, though the schistosity of surrounding Archean rocks has in places led to narrow zones of closely-spaced injected sheets of granite porphyry. The high-grade regional metamorphic and plutonic igneous nature of the host rocks has prevented the development of any obvious contact metamorphic effects.

The Mineral Park stock is believed to have been emplaced by a combination of forceful injection and piecemeal stoping. The structural guidance of folds and the planar flow structures at and near many of the contacts uphold the former. The presence of isolated pendants (?)

of the Cerbat complex in the interior of the stock supports the latter. In the Chloride district sill some stoping may have taken place, though spreading of the anticlinal layers conceivably could have provided the necessary space.

Age -- Injected as it is into pre-Cambrian schist and gneiss, the Ithaca Peak porphyry might be assigned to almost any geologic period. Schrader classified it as late Jurassic or early Cretaceous, and thought it to be of the same period of intrusion as the batholiths of California and western Nevada 38/. However, he also believed the intrusions to be allied with similar bodies in the Oatman district, some 25 miles to the southwest of Mineral Park. These were later mapped as intrusive into volcanic strata and assigned to the Tertiary 39/. A Tertiary age is assumed for the Ithaca Peak porphyry, in this report, on the basis of its close areal and structural relations with the Tertiary vein system in the Cerbat Range. These relations are discussed in the section on ore genesis.

GRANITE PORPHYRY DIKES

Vertical, or nearly vertical, tabular sheets of granite porphyry are scattered throughout the areas adjacent to the Ithaca Peak porphyry intrusions. They are profuse in the eastern part of the Chloride district. Although many of the sheets are concordant with the schistosity of the host rocks and should properly be called sills, for purposes of discussion they will be classed as dikes in this paper.

The dikes range in size from discontinuous sheets a few inches thick to layers as much as 200 feet thick and several miles long. Though many of the prominent dikes have an east-northeast strike, the major trend is northwest. Granite porphyry is common in one or both walls of the quartz-sulfide veins.

Some of the dikes form ridges, but most have no distinctive topographic expression. They are easily identified in the field by their appearance. All the dikes, both large and small, seem to have undergone some hydrothermal alteration and silicification, even where they are not in direct association with quartz veins. As a result, the dikes exhibit a bleached whitish to yellowish brown color, which stands out against the grays and blacks of the surrounding gneisses and schists.

Petrography -- A porphyritic texture in the dikes is provided by relatively few orthoclase phenocrysts, which, however, occur as crystals as much as several millimeters in length. A common textural variation is provided by the occurrence of small stringers, lenses, and pods of white pegmatite, which is apparently later in age but closely related genetically to the granite porphyry. The bulk of the rock is fine-grained and aplitic in hand specimen. A typical feature is the presence of brown limonite-stained joint lines and faces, with strong staining extending from the fractures into the rock as much as 1½ centimeters. Many of these fractures are lined with chalcedonic quartz.

Under the microscope the groundmass is revealed as an allotriomorphic aggregate of quartz, microperthitic orthoclase, and a few grains of microcline, with an average grain size of 0.6 milimeter. The feldspar is poikilitic with blebs of quartz and dusty magnetite (?). A few small aggregates of chlorite, quartz, magnetite, and limonite apparently have been formed from original biotite flakes. The preceding assemblage, with a few phenocrysts, composes approximately 75 percent of the rock. The remaining 25 percent consists of an interstitial mosaic of cryptocrystalline to microcrystalline quartz and orthoclase, accompanied by much sericite and murky brown limonite.

Quartz accounts for as much as 30 to 40 percent of the total composition. Much of this has been added hydrothermally, as shown by tiny seams of microgranular quartz which transgress feldspar grains but disappear in adjacent quartz grains.

Many of the dikes show weak gneissic structure. Observed foliation was parallel to the walls and was probably formed by planar flow. However, the possibility of secondary foliation is indicated by minor cataclastic crushing and granulation, seen under the microscope.

Age -- The granite prophyry dikes were injected shortly prior to or simultaneously with the introduction of the Ithaca Peak porphyry sill and stock, for none were found transgressing these intrusions.

PEGMATITE AND APLITE

Small dikes, lenses, and irregular masses of pegmatite, and small aplite dikes occur within the Ithaca Peak porphyry. They are more abundant in the Mineral Park stock than in the Chloride sill. The rocks are petrographically the same as the simple pegmatites and aplites in the Cerbat complex. They represent the first differentiation products that were injected following consolidation of the upper portions of the Ithaca Peak porphyry magma.

LAMPROPHYRE DIKES

Lamprophyres are present in numerous steeply-dipping to vertical dikes. These are located principally within and near the Ithaca Peak porphyry sill and stock, though examples occur as far away as the eastern base of the Cerbat range. Lamprophyres are common in the walls of quartz-sulfide veins.

VOGESITE

General Description -- Vogesite dikes occur in moderate number and excellent exposures exist immediately northeast of the Tintic mine, just west of the Mary Bell mine, and on the ridge northwest of the Minnesota-Connor mine. Most of the dikes follow a northwest trend. They are from

5 to 20 feet thick and normally can be traced for only a few hundred feet. However, the dike just west of the Mary Bell mine is 100 feet thick and extends more than half a mile. The rock is dense and resistant to weathering, and some of the dikes project as irregular ridges, rising 5 to 10 feet above the surrounding country.

Petrography -- Fresh specimens are dark gray to dark greenish gray, and weathered surfaces are light olive gray to brownish gray. Altered feldspar and hornblende are discernible under a hand lens. The rock almost invariably contains medium to coarse-grained, rounded crystals of quartz, accompanied in some specimens by crystals of orthoclase feldspar. These minerals appear to be xenocrysts and not original constituents of the rock, though it is possible that some of the feldspar crystals are phenocrysts. The occurrence of extraneous quartz and feldspar is not peculiar in view of the predominantly granitic nature of the country rock, and the embayed and corroded crystals probably represent the remains of granite fragments that were surrounded by the invading dikes. The majority of the xenocrysts measure only a few millimeters in diameter, although one specimen, from the dike just northeast of the Tintic mine, contains an orthoclase crystal 1 by 2½ centimeters in section.

Alteration products are normally so abundant that the determination of the rock is difficult. The texture is porphyritic, with a very fine-grained groundmass. Relatively unaltered portions of phenocrysts were determined as both orthoclase and plagioclase. In the groundmass, brown hornblende needles averaging 0.2 millimeter long are abundant. The borders, and often the entire crystals, are altered to a murky, brownish black substance. Orthoclase and plagioclase laths, also about 0.2 millimeter long, abundant apatite needles, and a few grains of magnetite make up the balance of identifiable primary minerals. There seems to be slightly more orthoclase than plagioclase. Large quantities of pale green chlorite, with calcite, sericite, kaolin, epidote, and zoisite, have formed as alteration products.

SPESSARTITE

General Description -- Spessartite dikes are numerous. They range from 18 inches to several feet in width, and most of them have a northwest trend. One dike, 5 to 6 feet wide, forms a low ridge immediately north of the Tennessee mine tailings dump. Other examples occur west of the Singlow claim, in the west wall of the Mayflower vein, and in association with the vein immediately south of the Copper Age mine.

Petrography -- The rock is brownish gray on weathered surfaces and is dark greenish gray where fresh. A characteristic feature of the rock is the development of large phenocrysts of hornblende and feldspar. Euhedral crystals 2½ to 4½ centimeters long, set in a fine-grained groundmass, are not unusual. In a portion of the dike west of the Singlow claim clusters of these phenocrysts form 50 to 60 percent of the rock. Most of the crystals are rounded and corroded.

A fresh specimen from the dike south of the Copper Age mine was examined under the microscope. Phenocrysts 1 to 5 millimeters in size compose 5 to 10 percent of this rock. In order of abundance, these consist of brown hornblende, augite, and completely altered feldspar. The hornblende occurs in two generations. In one the crystals are completely altered to a mixture of chlorite and epidote, whereas in the other the crystals are fresh. The augite is partly chloritized, and the feldspar is thoroughly saussuritized. Fresh feldspar phenocrysts from other specimens were determined as andesine (An_{40}). The relative abundance of hornblende and feldspar phenocrysts varies widely. In some specimens feldspar crystals are twice as numerous as are the hornblende crystals.

Most of the groundmass consists of laths of andesine approximately 0.1 millimeter long. They are typically arranged in sheaf-like clusters and are partly altered to calcite. Euhedral hornblende crystals make up 10 to 15 percent of the groundmass. These crystals average about 0.2 millimeter in length and are incompletely altered to epidote, calcite, and chlorite. Partly altered, equant grains of augite, 0.1 to 0.2 millimeter in diameter, are almost as abundant as the hornblende, and grains of magnetite, usually less than 0.1 millimeter, are numerous in the groundmass. Apatite needles are also common.

Xenocrysts of clear or milky quartz, as much as 6 millimeters in diameter, were observed in some specimens. The crystals are rounded and display narrow reaction rims.

KERSANTITE

A dike of kersantite occurs in the footwall of a short vein that strikes N 80 degrees W, and dips 76 degrees N, in the nose of the ridge immediately west of the Boulder Dam claim. The dike has a maximum thickness of 5 feet. It is pre-mineral in age.

Petrography -- The rock is a grayish brown where fresh, whereas weathered and hydrothermally altered specimens are dark greenish gray and very soft and punky. The texture is porphyritic, with a microcrystalline groundmass. Most of the phenocrysts are biotite plates averaging 2 millimeters in diameter. Some of the biotite is fresh and clear, but most of it is altered. Clear calcite is the chief alteration mineral, and the calcite is without exception partly or totally rimmed by narrow growths of fibrous brown chlorite. Feldspar phenocrysts, averaging 0.5 by 1.5 millimeters in section, are altered to calcite that is murky with an aggregate of sericite and other alteration products and is typically cut by veinlets of brown chlorite. The nature of the alteration products suggests that the original feldspar was a calcic plagioclase.

The groundmass, which consists of 0.01 to 0.04 millimeter grains, is about 30 percent fresh biotite, 10 percent magnetite granules, and the balance chlorite and calcite. A few crystals of sphene are present.

Age of Lamprophyres -- The lamprophyre dikes were injected after the consolidation of the Ithaca Peak porphyry and prior to the quartz-sulfide vein mineralization. Their time relationships with the volcanic dikes and extrusive rocks are not known. Though the different varieties are thought to be closely related in origin, and therefore of about the same age, the vogesites seem to have preceded the spessartites, as a dike of the latter cuts a vogesite dike in the area west-northwest of the Singlow claim. The relative position of the kersantite has not been determined.

TERTIARY ERUPTIVE ROCKS

Volcanic strata once probably covered the entire Chloride quadrangle. Remnants occur west of Chloride and discontinuously along the east flank of the range. The oldest eruptive rocks are flows, tuffs, and breccias predominantly andesitic in composition. These rocks rest upon a surface cut on the pre-Cambrian Cerbat complex. They are termed the Bull Mountain series, as they form the impressive cap-rock of that peak. Overlying these basal andesites, with apparent disconformity, are rhyolite tuffs, breccias, and flows. They are designated the Kingman series, as they are best exposed in and around Kingman. West of Chloride, on the north side of the mouth of Big Wash, an andesite flow lies unconformably on rhyolite tuff and breccia. This "Big Wash andesite" was not observed elsewhere in the area mapped.

Age -- These volcanic extrusions have previously been assigned to the Tertiary by Schrader 40/ and Lee 41/. There is no proof that all of them are Tertiary. Lacking evidence to the contrary, however, their inclusion as part of the Tertiary volcanic system so widespread over the Basin and Range province is believed reasonable.

BULL MOUNTAIN SERIES

The Bull Mountain series of flows, tuffs, and breccias occurs only along the east side of the range. They were not studied in detail, as the mapping in this area was done rapidly, with the purpose of determining only general rock distribution and structure. The series covers several square miles in the southeastern part of the quadrangle. This area is the northernmost extension of the large volcanic mass known as the Kingman Mesa, and the topography is that of a well dissected, block-faulted table-land. The strata reach a thickness of almost 1,000 feet in this section, hundreds of feet being exposed in sheer cliff faces. The beds strike predominantly northeast and dip at low angles to the southeast. Farther to the north the Bull Mountain series occurs as isolated small cappings of ridges and buttes, with a maximum thickness of 350 feet.

The series consists mostly of flows of medium gray to grayish red purple andesite, with some dark gray basalt members. Intercalated with the flows, and especially abundant in the basal section, are beds of pink and red scoriaceous breccia and yellow to red tuff and lapilli.

In every place where the basal beds are exposed they lie upon an almost flat surface of pre-Cambrian rocks. The maximum relief observed in this surface is not over 50 feet. (See Figures 14 and 15). The surface and the superimposed volcanic strata dip at low angles away from the mountains. In the southern part of the range the dip is southeast, whereas north of Vock Wash it is northeast. In places the volcanic rocks pass beneath the alluvium of the Hualpai Valley.

If detailed mapping were done, the series must be divided into at least two units, for, after an initial period of volcanic activity, the beds in some places were cut by faults and the uplifted portions were removed by erosion. The maximum observed displacement in this faulting is only 250 feet, and the period of erosion was sufficiently long to restore a flat survace. The remaining beds were then covered by a later sequence of andesitic material. Any tilting which accompanied the faulting must have been slight, as no distinct angular unconformity exists between the lower and upper strata.

In several places the Kingman rhyolite series overlies the Bull Mountain series with concordant attitudes. However, in the section north of Vock Wash, faulting and erosion of the andesitic strata seem to have taken place prior to the extrusion of the rhyolite, and the relationships are disconformable, at least in that area. This period of faulting and erosion might represent the intra-Bull Mountain series break, if the upper andesitic beds had not been deposited or had been stripped away prior to the outpouring of rhyolite. However, the faulting and erosion is thought more likely to have occurred after cessation of andesitic volcanic activity and to represent an inter-volcanic break.

Most, if not all, of the volcanic exposures along the east side of the range have been preserved by down-dropping along northwest trending normal faults, which are later in age than the Kingman rhyolite series.

<u>Correlation of Bull Mountain Series</u> -- The Bull Mountain series corresponds to the "older andesite" of Lee <u>42/</u>, and occupies the same

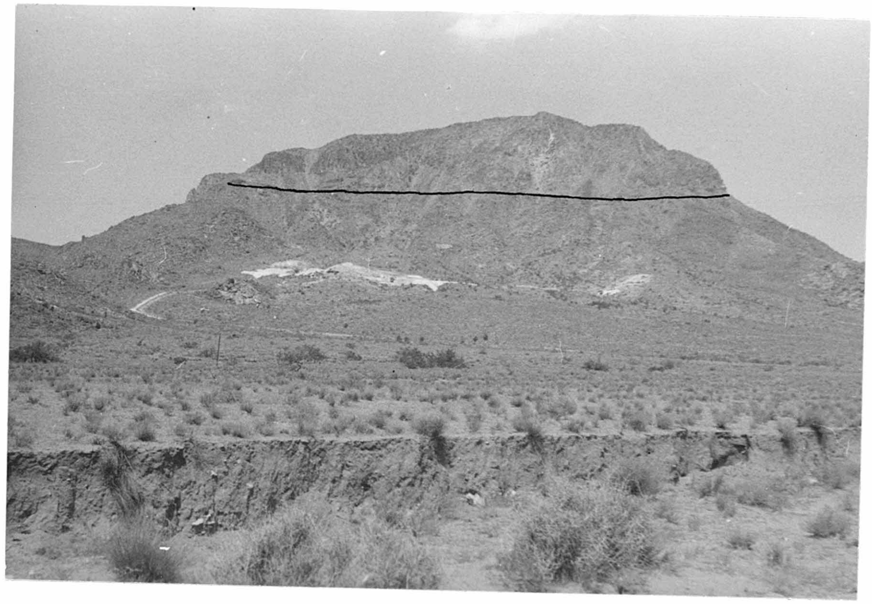


Figure 14 -- East face Bull Mt., showing Bull Mountain volcanic series resting on almost flat surface of Cerbat complex. Consolidated Feldspar Corporation workings in center of picture.

Figure 15 -- Ridge, SE corner Chloride quadrangle. Bull Mountain volcanic series resting on surface of low relief of Cerbat complex. View looking west.

stratigraphic position as the Alcyone and Esperanza trachytes, Oatman andesite, and Gold Road latite of the Oatman district in the Black Mountains 43/.

KINGMAN SERIES AND BIG WASH ANDESITE

CHLORIDE DISTRICT

Small patches of stratiform volcanic rocks occur along the western edge of the Chloride district, on the down-dropped side of the Sacramento fault (See Plate 1). The beds have a northwest strike, dip at varying angles to the southwest, and form a series of isolated low hills along the fault line. The volcanic rocks disappear to the west beneath the alluvium of the Sacramento Valley and tongues of alluvium separate the hills.

Kingman Series -- Explosive rhyolitic products of the Kingman series are the oldest exposed volcanic rocks. Several different beds can be distinguished, all conformable, with a strike of N 50 to 60 degrees W, and a dip of 25 to 30 degrees southwest. Inasmuch as the Sacramento fault, against which the beds terminate, strikes N 45 degrees W, and the beds dip away to the southwest, the lowest strata should occur farthest to the north along the fault line. However, this cannot be relied upon, as auxiliary faulting, at high angles to the Sacramento fault, has broken the stratigraphic continuity.

Petrography -- The two northernmost mapped exposures contain a visible section approximately 700 feet thick, composed of coarse reddish breccias. The rocks are distinctly stratified and well consolidated.

In the three exposures to the south several hundred feet of strata must be represented, but the maximum thickness of any one section is about 80 feet. Three rock types are present. The lowest and thickest is a loosely consolidated grayish yellow to light brown tuff that is massive in hand specimen. It is light, porous, and can be dented easily with a pick. Essentially a vitric-lithic tuff, it is composed mostly (90 to 95 percent) of pumice fragments which vary in size from a few tenths of a millimeter to 1½ centimeters. The remainder of the rock consists of angular, accidental rock fragments which vary from 1 millimeter to 2½ centimeters in greatest diameter. Most of these fragments are gray to reddish porphyritic andesite, but a few are light gray porphyritic rhyolite. Sparse, isolated crystals of feldspar occur in some specimens.

Overlying the unconsolidated tuff is a bed of welded tuff, 10 to 15 feet thick. Hand specimens of this are pale yellowish brown to grayish red, with a streaked and layered structure that is visible even in tiny fragments. The streaks consist of compressed blebs of black volcanic glass. In some places there are distinct beds of vitrophyre a foot or more thick. The rock is compact and breaks with a rough conchoidal fracture.

Under the microscope a compressed and welded vitroclastic texture is visible. The percentages of the constituents vary, depending on the amount of obsidian present in a bed, but the bulk of an average specimen consists of distorted glass shards which range from 0.1 to 0.5 millimeter in size. These have a refractive index of approximately 1.504, which, on the basis of George's tables 44/, indicates a rhyolitic composition. The central portions of the larger shards, and the entire smaller fragments, are partially devitrified and are a clear yellow, with a faint gray birefringence. All the shards show the effects of flattening and elongation, and some are bent around isolated crystals of feldspar.

Fragments of collapsed pumice and flattened blebs of obsidian are abundant. These fragments may be less than 1 millimeter to over 1½ centimeters long, and 0.1 millimeter to 3 or 4 millimeters wide. Tiny complicated folds occur in the pumice, and both the pumice and obsidian are devitrified along fine lines parallel with the general banding. Some of the smaller fragments and parts of the larger ones are devitrified to a cryptocrystalline mosaic of quartz (?) and feldspar (?). Some of the obsidian is porphyritic, containing euhedral grains of sphene and magnetite, plates of biotite, and resorbed crystals of sanidine and oligoclase. A few tiny spherulites and crystallites are also present.

Discrete crystals that must have been explosively separated from the original magma are common. They include biotite, sanidine, oligoclase, quartz, and small grains of magnetite, most of which is altered to hematite. Accidental crystals of andesine, labradorite, light green augite, and hypersthene occur in most specimens. Accidental rock fragments of gray to reddish porphyritic andesite are not unusual. These occur as small angular pebbles and display no effects of deformation or flattening. Phenocrysts of andesine, labradorite, augite, and hypersthene, set in a pilotaxitic to hyalopilitic groundmass, point to a common andesitic source for both the accidental free crystals and the rock fragments. Resorption effects on some of the pebbles suggest that the andesite fragments were included in the rhyolitic magma prior to its ejection.

Above the welded tuff, but with what seem to be gradational relationships, lies a reddish brown tuffaceous breccia. A maximum thickness of approximately 30 feet of this breccia is exposed beneath a basalt capping. The rock is composed of fragments of pumice from 2 to 4 centimeters in diameter, set in a matrix of pumiceous ash and small lapilli. Numerous accidental fragments of andesite, 2 to 10 millimeters in size, are also scattered through the rock. The pumice and andesite fragments are essentially the same in composition as those in the welded tuff, and the pumice fragments in the breccia are collapsed into wafer-like forms. The chief distinction between the breccia and the welded tuff lies in the degree of coarseness.

Devitrification is more advanced in the pumice of the breccia than in that of the welded tuff, and calcite and tridymite are abundant in the groundmasses of both pumice and andesite fragments that occur in the breccia.

Big Wash Andesite -- A flow of andesite 50 to 60 feet thick unconformably overlies the pyroclastic rhyolite beds in the northernmost mapped exposures of volcanic rocks. The andesite strikes N 45 degrees W, essentially parallel to the course of the Sacramento fault, and dips about 15 degrees to the southwest. Platy jointing is well developed in the bed and is expressed through the development of ledge-like outcrops.

Petrography -- The andesite is medium light gray and weathers to a light brownish gray. It is vesicular, amygdaloidal, and porphyritic. Abundant euhedral laths of feldspar are visible megascopically. The most numerous feldspar laths, which range from 1½ to 5 millimeters in length, are andesine (An_{40}). Many are concentrically zoned, however, with centers of andesine and rims of oligoclase (An_{30}), and less numerous laths, 0.2 to 1.0 millimeter in size, consist entirely of oligoclase. All the feldspar phenocrysts exhibit effects of resorption.

Crystals of light green augite, as much as 1 millimeter long, occur in small amount. Hypersthene grains, 0.3 millimeter in average length, are a little more abundant than augite. The hypersthene is invariably partly altered to pale green bastite, and some grains are completely altered. Irregular grains of magnetite, 0.1 to 0.3 millimeter in diameter, are abundant.

The groundmass has a microcrystalline pilotaxitic texture and consists of a densely felted mass of tiny untwinned feldspar laths, with many interstitial grains of magnetite, some of which are altered to hematite. A few needles of apatite and granules of augite are also present.

Cristobalite, filling vesicles, is invariably present, and calcite occurs in some specimens.

History -- All the rhyolite along the Sacramento fault is pyroclastic. Although the exposures are limited, the beds are thick, and extensive volcanism is indicated. Following their deposition, the rhyolite beds were tilted to the southwest about 15 degrees. A long enough period of erosion followed to permit thorough planation. The rhyolite was then unconformably covered by a flow of andesite. Later tilting brought the andesite to an average dip of 15 degrees southwest and the rhyolite beds to about 30 degrees. The late tilting was probably a function of movement on the Sacramento fault. The beds occur on the down-dropped side of the fault and drag easily could have produced the present attitude of the andesite and part of the dip in the rhyolite. The early tilting of the rhyolite, however, cannot be explained in this fashion, for the beds strike into the fault. Deformation not related to the Sacramento fault must have occurred, and the initiation of the Sacramento fault must have taken place in a late stage of the regional geologic history.

EAST SIDE OF CERBAT RANGE

The remnants of the Kingman rhyolite series, which overlie the Bull Mountain series along the eastern flank of the range, contain the same types of loosely compacted tuffs, breccias, and welded tuffs that occur in the Chloride district. However, the sections are thinner, 300 feet being the observed maximum, and rhyolite flows are present in addition to pyroclastics. These flows are light gray, with a vitrophyric texture and a pronounced flow structure. Phenocrysts are sanidine, and a few crystals of orthoclase, oligoclase, quartz, biotite, hornblende, zircon, and sphene. The groundmass is partially devitrified to a cryptocrystalline mosaic.

A further difference is in the degree of tilting of the rhyolite beds. Deformation has not been as strong on the east side of the range, and the beds dip only 6 to 8 degrees.

Younger andesite, comparable to the Big Wash andesite flow, is not present in the part of the eastern section that was mapped.

Correlation of Kingman Series and Big Wash Andesite -- The Kingman series corresponds to the young rhyolite series of the Black Mountains, described briefly by Schrader 45/ and discussed as the Antelope rhyolite and Sitgreaves tuff by Lausen 46/. The Big Wash andesite correlates with the "younger andesite" of the Black Mountains 47/, and similar strata are mentioned by Lee as occurring in the White Hills, Kingman Mesa, and Aquarius Mountains 48/.

QUATERNARY OLIVINE BASALT

Capping all the mapped exposures of volcanic rocks along the Sacramento fault are sheets of olivine basalt 10 to 25 feet thick. These sheets are flat to gently dipping southwest and lie unconformably on the older rocks. Portions of the basalt layers rest on and interfinger with the Quaternary gravels, and in one place the basalt seems to lie unbroken across the Sacramento fault. Reddish to black scoria is abundant in the basalt areas, and a few volcanic bombs were observed.

Petrography -- The basalt is dark gray where fresh and weathers to a grayish or dusky brown. It is vesicular and in some places contains amygdules of clear calcite. The texture is porphyritic with phenocrysts of olivine and augite. The groundmass has an intersertal texture and is composed of a dense felt of labradorite laths and scattered grains of magnetite, augite, and olivine, all set in a matrix of dark brown glass.

Age -- The older volcanic rocks had been deposited, block-faulting and extensive erosion had determined the present configuration of the mountains, and large amounts of alluvium had collected prior to the extrusion of basalt. This is shown by the fact that the basalt overlies and interfingers with the alluvium and also overlies the Sacramento fault, which cuts the underlying volcanic rocks. It can be assigned with little question to the Quaternary. Sheets of basalt in the Black Mountains, of similar nature and stratigraphic position, have been included in the Tertiary by Lausen 49/.

VOLCANIC DIKES

RHYOLITE

Rhyolite dikes are numerous in all the mineralized areas. Small dikes are scattered throughout the Chloride district, many of them occurring in the walls of quartz-sulfide veins. One very large dike, (See Plate 1), is prominent in the eastern, highest portion of the area. This dike, which strikes N 25 degrees E, and dips steeply to the west, varies from 50 to 200 feet in width and is more than 2 miles long. It crops out in the saddle immediately north of the Lucky Boy mine, runs through the ravine below the Samoa-Brighter Days camp, and passes on south into the Mineral Park district, where it cuts the Ithaca Peak porphyry.

A distinctive zone of thick, steeply-dipping rhyolite sheets, striking N 20 degrees W, cuts through the center of the Ithaca Peak porphyry stock. This zone is as much as one-quarter of a mile wide and is more than four miles long. Thick dikes in this zone are exposed at the gateway to the Mineral Park basin and near the Oro Plata mine in Todd Basin. Several prominent rhyolite dikes, striking about N 40 degrees W, occur near the mouth of Cerbat Canyon. Some of the dikes form strong ridges, whereas others have no topographic expression. A dike that cuts the peak just northeast of Gross ranch has eroded to form a trench through the top of the peak.

Petrography -- The rhyolite is yellowish gray, and most specimens are megascopically porphyritic. Many dikes are moderately to strongly silicified.

In the two specimens examined under the microscope, the rhyolite exhibits a cryptocrystalline to microcrystalline porphyritic texture. The phenocrysts are mostly orthoclase and microcline, occurring as well rounded crystals as much as 1 by 2.5 millimeters in section. Carlsbad twins are common, and some of the phenocrysts are poikilitic with inclusions of sagenitic quartz, muscovite, apatite, and zircon. Rounded grains of quartz also occur as phenocrysts but are not abundant. The groundmass consists of approximately 70 percent orthoclase and 30 percent quartz. Scattered crystals of zircon occur in the groundmass, and sericite is abundant in the orthoclase. Veinlets of microcrystalline quartz cut the specimens examined, and the sericite, and perhaps some of the quartz in the groundmass, may be of hydrothermal origin. No mafic minerals were observed in any of the dikes, either microscopically or megascopically.

Chemical analyses would be necessary to determine the composition of the dikes, but the microscopic examination suggests that they are high-potash dikes, similar to those in the Homestake Mine, Lead, South Dakota, described by Noble 50/.

Age -- Rhyolite dikes occur within the Ithaca Peak porphyry and therefore are later in age. Their relative position with respect to the lamprophyre dikes was not determined. It is assumed that the rhyolite dikes were intruded in Tertiary time, as part of the Tertiary volcanic system of the Basin and Range province. Correlation with the extrusive Kingman rhyolite series might be possible if compositional similarity could be demonstrated. In view of the high-potash content of the dikes, however, this does not seem likely. The silicification and the truncation of some of the dikes by quartz-sulfide veins indicate that the rhyolite is pre-mineral in age. No rhyolite dikes were observed to cut the veins.

ANDESITE

A few small andesite dikes cut both the Cerbat complex and the Ithaca Peak porphyry. These dikes range from 6 inches to 4 feet in width, and some of them project as low ridges above the surrounding rocks. None could be traced more than a few hundred feet.

Petrography -- The rock is dark greenish gray to dark gray. It has a porphyritic texture, and a microcrystalline hyalopilitic to intergranular groundmass. Phenocrysts of labradorite (An_{55}) make up about 5 percent of the rock. These occur as euhedral, slightly resorbed crystals, 0.3 by 1.5 millimeters in average section. Some have good concentric zoning, being more sodic on the edges. Most phenocrysts are fresh, but part or complete alteration to a mixture of chlorite, zoisite, epidote, and albite, accompanied by sericite and kaolin, occurs in some.

About 60 percent of the groundmass consists of a felt of andesine laths, which average 0.15 millimeter in length. The laths are fairly fresh, though alteration similar to that in the phenocrysts is present. Interstitial to the laths are green chlorite and grains and rods of magnetite, partly altered to hematite. The shape of some grains suggests that the chlorite was derived from pyroxene.

Some dikes are associated with quartz-sulfide veins and are thoroughly propylitized. Specks of disseminated pyrite, of hydrothermal origin, are common in these altered dikes.

Age -- The dikes are possibly related to the extrusive volcanics, and are presumed to be Tertiary in age. Similar to the rhyolite dikes, they are later in age than the Ithaca Peak porphyry, but of undetermined position with respect to the lamprophyres. No exposures were found in which the sequence of introduction of the rhyolite dikes and andesite dikes could be ascertained. The occurrence of andesite in the walls of veins, with attendant propylitization, indicates a pre-mineral or, at the latest, an inter-mineral age for the dikes.

BASALT

A small olivine basalt dike occurs in the western part of the Ithaca Peak porphyry sill, half a mile north of the town of Chloride. A larger basalt dike, 8 to 10 feet wide, cuts the Cerbat complex in the hillside due west of Merit Spring. It is highly vesicular and amygdaloidal in places. Aside from dating the small dike as post-Ithaca Peak porphyry, no age determinations can be made. The dikes may be Tertiary and related to the basaltic rocks of the extrusive Bull Mountain series, or they may be Quaternary and related to the basalt flows that interfinger with alluvium. The dikes are similar in appearance and composition to flows of both ages.

ALLUVIUM

The alluvium in the region is composed of the detritus that covers the bottoms of the canyons and washes, the fill of the Sacramento and Hualpai Valleys, and the terrace deposits that occur along the walls of many canyons. The detritus now in transit down the slopes and along the drainage-ways is of course Recent in age, and consists of a loose mixture of current erosion products. The terrace deposits represent older alluvium, as does the bulk of the detrital apron flanking the range. The Sacramento Valley apron has been dissected, with the exposure of older debris. The Hualpai Valley apron is only locally dissected, and the older fill is mostly covered with Recent wash.

The terrace beds and dissected portions of the aprons reveal a poorly sorted accumulation of angular to sub-rounded sand, pebbles, cobbles, and boulders representing all the rocks of the Cerbat range. Boulders 10 to 15 feet in diameter are not uncommon, though cobbles 1 to 5 inches in diameter predominate. A poorly defined stratification exists in some places, as do distinct beds of sand and silt. The deposits are largely unconsolidated, but terraces in the Mineral Park district have been cemented by iron oxides, and white to brown caliche has served as a weak binding agent in places in the valley fill. Another type of cementation has occurred in the alluvial veneer that covers the pediment area west of Mineral Park. There mineralizing solutions have bound the debris together in a blanket that forms the Emerald Isle copper deposit. Isolated thin sheets of olivine basalt overlie and interfinger with the alluvium in the Sacramento Valley west of Chloride.

The alluvium began to collect following the initial elevation of the Cerbat Range. This event cannot be dated accurately but probably took place in the late Tertiary. Large amounts of detritus accumulated, probably continually stimulated by progressive lifting of the mountain block, and aggradation in the adjoining basins continued into the Quaternary epoch. A late period of aggradation along the canyons within the range is indicated by alluvial terraces. In comparatively recent time a period of degradation was inaugurated. This seems to have been due to a regional eastward tilt, for rejuvenation effects are well shown in the canyons draining the west slope of the range and in the adjoining Sacramento valley apron, whereas aggradation was only locally interrupted along the east side of the range. Terraces within the mountains are from 25 to 50 feet above present stream levels (See Figure 16), while incised washes along the edge of the Sacramento valley are as much as 50 feet below the adjacent surface. The stripping of debris along the western base of the mountains has exposed wide bedrock pediment areas, many of which contain veins. In other areas veins probably remain concealed.

The older alluvial deposits can be correlated with the Temple Bar conglomerate, which has been assigned to the Pleistocene by Lee 48/.

GEOLOGIC STRUCTURE

General Features -- The Cerbat range is a rigid, massive block consisting almost entirely of crystalline schist, gneiss, and granite. Remnants of folds, however, are preserved in this rigid crystalline complex and indicate orogenesis in pre-Cambrian time.

Foliation is developed to varying degrees in all the plutonic and metamorphic rocks, and three joint systems cut all the rocks without discrimination as to type or age.

Faulting that must have occurred in the pre-Cambrian is difficult to detect. Mylonitic zones testify to movement by intense shearing, but the dislocations cannot be dated. Minor movement preceded or accompanied the injection of some of the silicic and mafic dikes, and a period of faulting is evident in the formation of the numerous veins. Four distinct

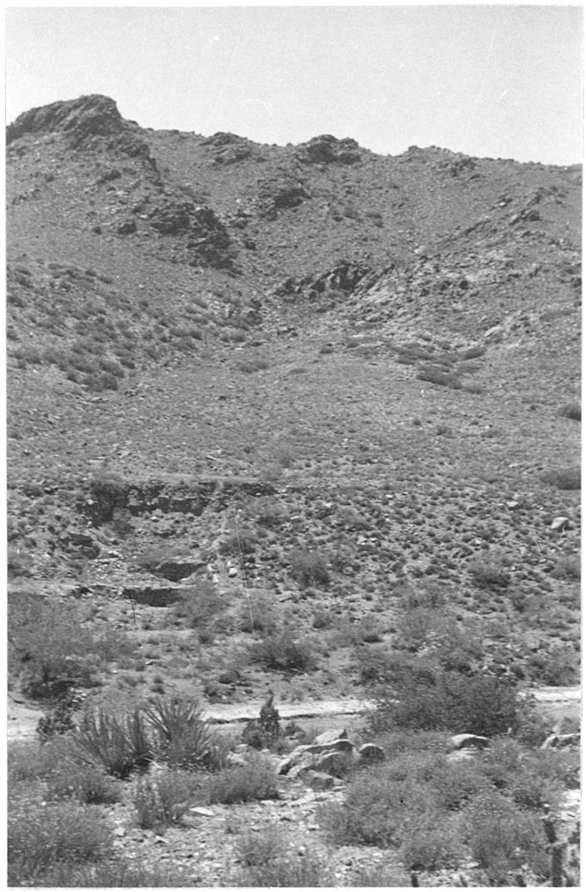


Figure 16 -- Terrace on west side of Mineral Park wash, just south of Nigger Head. Terrace level approximately 30 feet above present level of wash.

fracture periods occurred during mineralization, and strong post-mineral brecciation is visible in many of the veins. At least two and possibly four ages of normal faults are shown by remnants of Tertiary volcanic strata. Delineation and elevation of the Cerbat range has occurred along the youngest of these normal faults.

ARCHEAN FOLD SYSTEM

An orogenic fold system must, at one time, have covered this entire region. Most of the folds have been obliterated ~~but~~ by processes of granitization and batholithic intrusion, but a few remnants still exist.

The largest fold is an anticline that occupies the western half of the Chloride district. Its presence is revealed by the disposition of the crystalline metamorphic and igneous rocks in steeply-dipping, concordant, curved layers. The axis of this anticline strikes about northeast and plunges about 60 degrees, forming a symmetrical fold. Once established, this fold guided the series of igneous intrusions which followed, and which now form the bulk of the rocks in the structure. During pre-Cambrian time the core of the arch was occupied by coarsely porphyritic Diana granite, and sheets of pegmatite were injected into the limbs. At a later date, possibly in the Tertiary, a sill of Ithaca Peak porphyry was introduced into the flanks of the anticline, forming an additional curved igneous layer.

A smaller but well-defined anticlinal remnant is marked by the distribution of septa in the northwest side of the Ithaca Peak porphyry stock in the Mineral Park district. The axis seems to strike north-northeast and plunge 75 degrees northeast. However, only the nose and northwest limb are preserved, and the axial position is difficult to fix. The fold is at least two miles wide, with the strata either vertical or steeply dipping outward. It guided the emplacement of the northwest portion of the Ithaca Peak porphyry stock, and planar flow structure in the latter developed a mimetic anticlinal pattern (See Figure 17). Isolated attitudes suggest that an asymmetrical, almost isoclinal, narrow syncline exists betwen this anticline and the large one in the Chloride district.

In the area including the southwest end of the Ithaca Peak porphyry stock and the northwest portion of the Cerbat district, an anticline is suggested by the configuration of the border of the stock and by the attitudes of foliation, both in the stock and in the rocks of the Cerbat complex. The trend of the structure is northeast, and it plunges to the northeast. Minor anticlines and synclines seem to be present, and the entire structure is slightly overturned to the southeast.

A small anticlinal nose, only visible for a few hundred feet, is exposed in the canyon on the north side of Bull Mountain. This fold strikes north-northeast and plunges 12 degrees northeast. Another small anticline was observed in the ridge approximately 1½ miles due east of the Stockton mine. This fold strikes north-northeast and plunges 70 degrees northeast.

Away from areas where distinct folds are present, foliation attitudes have an average trend of N 40 degrees E. Aside from vertical layers, about 80 percent of the observed attitudes have dips of 75 to 80 degrees to the northwest, the balance dipping steeply southeast. This implies the existence of formerly extensive isoclinal folds, the remnants of which are now overturned 5 to 15 degrees to the southeast. This overturning may be due in part to original compressive stress. However, at least some and possibly all of it is the result of eastward tilting of the mountains in Tertiary time. This tilting is also responsible

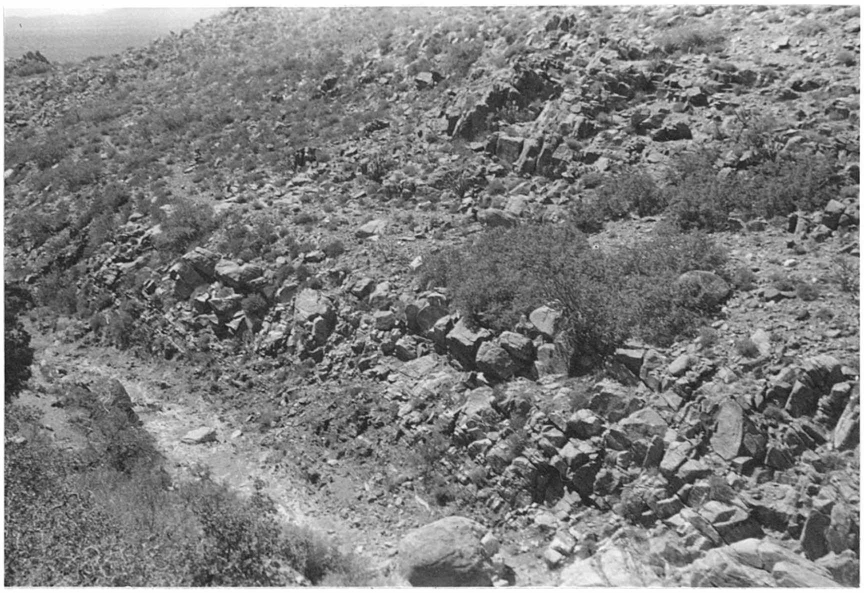


Figure 17 -- Canyon, northwest corner Ithaca Peak porphyry stock (Center S 14, T 23 N, R 18 W), showing planar flow structure developed parallel to nose of pre-existing anticline. View looking west-northwest.

for some of the plunge of the anticline remnants.

No true drag folds were observed, but ptygmatic folds are numerous. These seem to have formed under conditions of active major folding, for their axial planes are approximately parallel to the foliation of the enclosing rocks. Inasmuch as the foliation seems parallel to original bedding, a certain amount of inter-bed shearing must have aided in the formation of the ptygmatic folds.

A consistent feature is the northeast to north-northeast strike of the regional structure lines. Though batholithic intrusion and granitization destroyed much of the continuity, the trend was not disturbed.

FOLIATION

Pre-Cambrian rocks -- Foliation in the Cerbat complex ranges from the excellent flow cleavage of the biotite schists to faintly gneissic granite. A few areas of massive granite exist, but they are minor in extent. In the anticline remnants, foliation of the schists seems to be parallel to original bedding, for it wraps around the noses of the folds. The foliate structure possibly developed through a combination of mimetic recrystallization and flow parallel to the bedding, induced by intense hydrostatic and horizontally directed compressive stress and associated extreme temperatures of high-grade regional metamorphism. The foliation of the layers of gneiss, which also parallels the original bedding, could either be due to primary planar flow, be inherited from pre-existing schists by a process of granitization, or be due to compression. Whatever the cause, and more than one may have operated in any one place, the fold pattern was followed faithfully.

On the grounds of this conformity to structure in the remnant anticlines, it is assumed that most of the foliation in the Cerbat complex, especially in the layers of schist, is essentially parallel to original bedding. This assumption is the basis for deducing isoclinal folding in the areas where the foliation has a consistent N 40 degree E strike and a steep dip to the northwest.

Much of the gneiss shows effects of cataclastic deformation, imposed after the consolidation of the rock and after or near the end of orogenic folding. Some of the gneissic foliation is due to this later stress. Transection of earlier foliation might be expected but was not observed. The continuing or revived compression must have been unchanged in direction and relieved in such a way that younger foliation merely added to the intensity of older or was formed parallel to it. In plutons, such as the Diana granite, secondary foliation in the interiors of the masses has, in most places, a northeast strike and steep dip, parallel to the regional grain.

Secondary lineation is present in the hornblende schists. In the few observations that were made, the long axes of the hornblende crystals seemed to be parallel to the axes of associated folds. No attempt was made to apply methods of structural petrology to the schists. Such a study would undoubtedly add much information on the tectonic history and on the nature of the deforming forces in pre-Cambrian time.

Ithaca Peak Porphyry -- Primary planar flow structure is well developed in many places along the borders of the Ithaca Peak Porphyry sill and stock. The flow structure is parallel to the contacts and is characteristically strongest immediately adjacent to the contacts. This parallelism is its diagnostic feature. Primary foliation is especially well shown between the anticlinal septa in the northwest portion of the Mineral Park stock (See Figure 17). It is not uniformly developed, and border areas may be massive or only slightly gneissic.

Compressive forces, possibly contemporaneous with and definitely outlasting consolidation of the Ithaca Peak porphyry, caused secondary foliation which differs in degree from place to place. It is best developed in the Chloride district sill. Local secondary foliation occurs in the Mineral Park stock, but the bulk of the intrusion is massive. The compressive forces were from the northwest or southeast, for most of the foliation strikes about N 50 degrees E, and has vertical to steep dips. This predominating trend is shown in Figure 18, which is a point diagram prepared in the manner outlined by Billings 52/. This technique, which utilizes the plotting methods of structural petrology, shows the poles of perpendiculars to surfaces such as folia, joints, and veins. Perpendicular surfaces are represented by points on the circumference of the plotting circle, and horizontal surfaces are represented by a point in the center. In Figure 18 both primary and secondary foliation have been plotted. This has not altered a dominant northeast strike. The reason probably is that the contacts of the long western limb of the Chloride sill, as well as the contacts of the northwest part of the Mineral Park stock, have a northeast strike, and the primary foliation parallel to these contacts provided a large portion of the total observations.

JOINTS

Pre-Cambrian rocks -- A complex set of stresses must have acted in the creation of fracture systems in the pre-Cambrian. Horizontal compression is evidenced by the folding, strong hydrostatic pressure would be a factor in the high-grade regional metamorphism, and thermal expansion and contraction necessarily would be associated with the intrusion of the igneous rocks. In addition, stresses of all later geologic periods might develop fractures in these ancient rocks.

The resulting joints are therefore complex but can be resolved

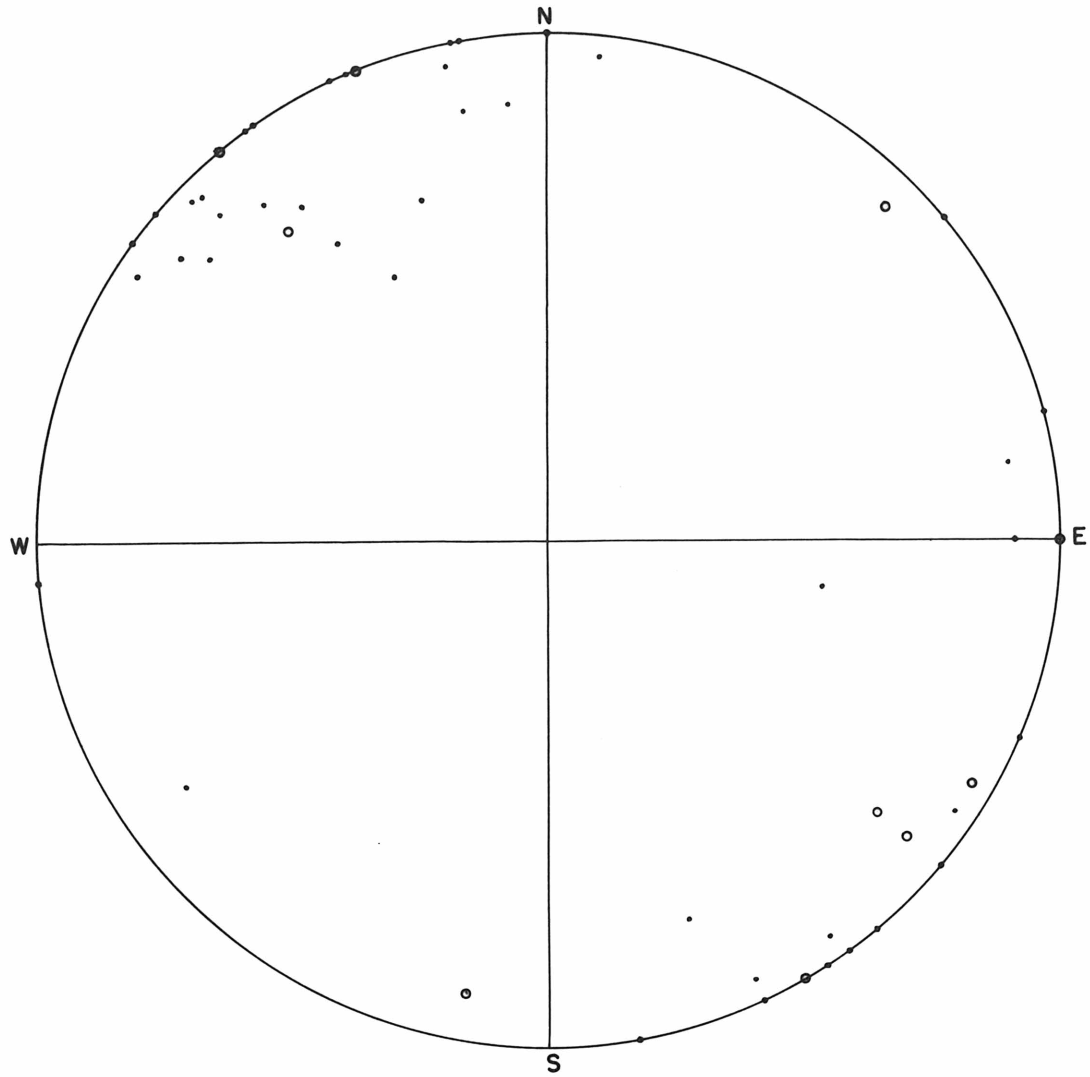


Figure 18 -- ITHACA PEAK PORPHYRY FOLIATION

Point diagram, showing poles of perpendiculars to 53 foliation surfaces in the Ithaca Peak porphyry. Plotted on upper hemisphere. Equal area projection.

• Chloride district sill.
o Mineral Park stock.

into three trends, which are exhibited in both the early schists and in the later granite and gneiss. This leads to the conclusion that directional stress, having a uniform orientation both in the pre-Cambrian and later ages, was the principal factor in the establishment of the joint pattern. In field observations the joints were recorded as strong, moderate, or weak. A joint was classed as "strong" if it seemed to extend beyond the area of observation, and if there were numerous parallel joints. A joint was considered "weak" if it seemed to be small, and if there were few parallel joints. A joint between these extremes was called "moderate". In most places, moderate joints were recorded only where stronger joints were also present, to use in comparison. The terms are relative and the classification can change with distance. However, in plotting the joints, correlation was obtained between directional trends and relative strength. The attitudes of joints, segregated according to relative strength, are shown in Figures 19, 20, and 21. These are point diagrams similar to that of Figure 18. The strongest joints strike about northwest and in general dip very steeply. This is demonstrated by the massing of points in the mortheast and southwest quadrants of Figure 19. Joints with dips to the northeast are most numerous, but a set that dips to the southwest is noticeable. The moderate joints (See Figure 20) display less consistency in direction, but a northeast strike is favored. Steep dips to the southeast are most numerous, but a set that dips to the northwest is present. The weak joints are scarce and give a scattered point diagram (See Figure 21). Field observations show, however, that where three different joints occur together there is a tendency for the weakest set to strike to the north. Dips are either east or west.

The orientation of folding and foliation indicates that the compressive forces affecting the pre-Cambrian rocks were oriented about

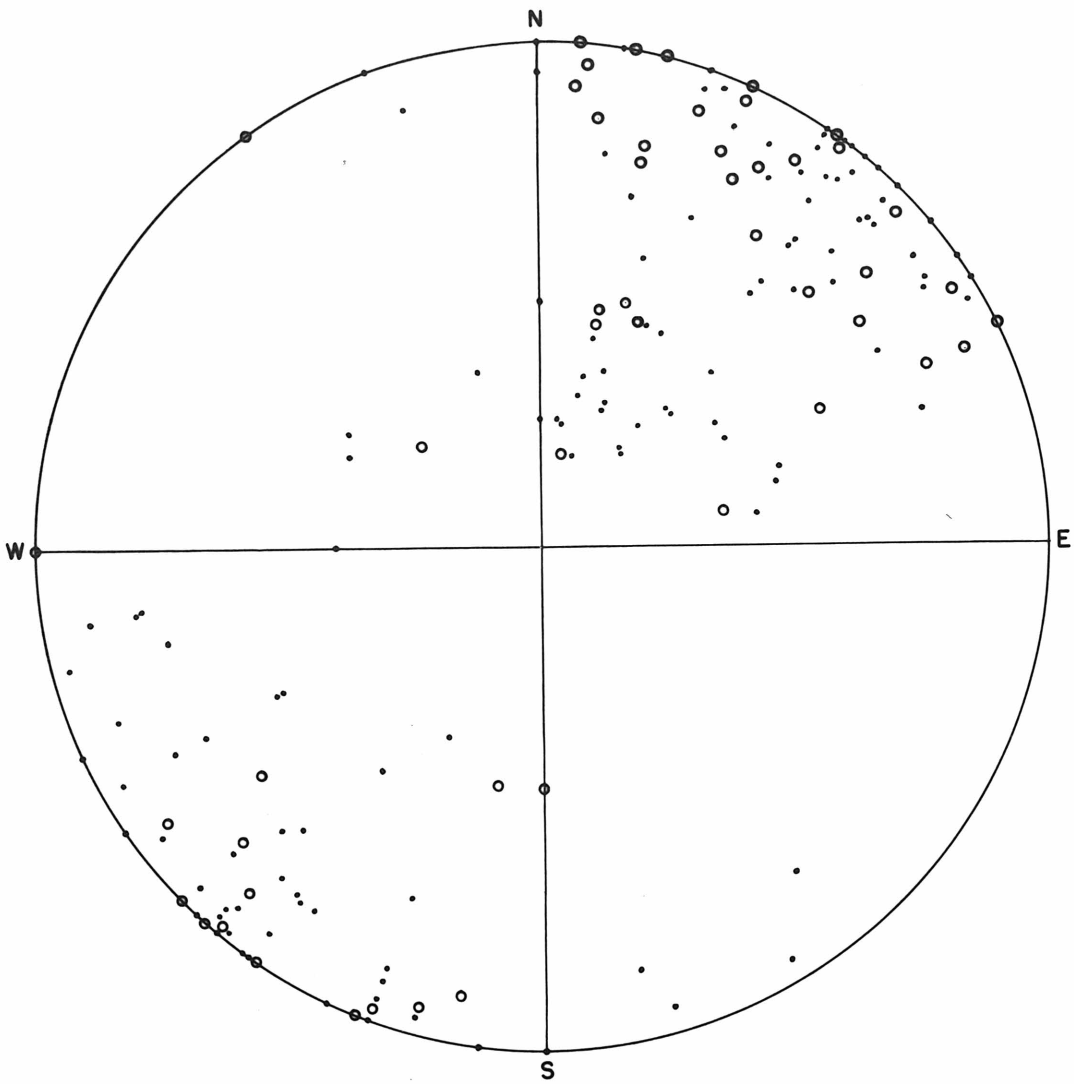


Figure 19 -- STRONG JOINTS

Point diagram, showing poles of perpendiculars to 175 strong joints. Plotted on upper hemisphere. Equal area projection.

- • Joints in Cerbat complex.
- ∘ Joints in Ithaca Peak porphyry.

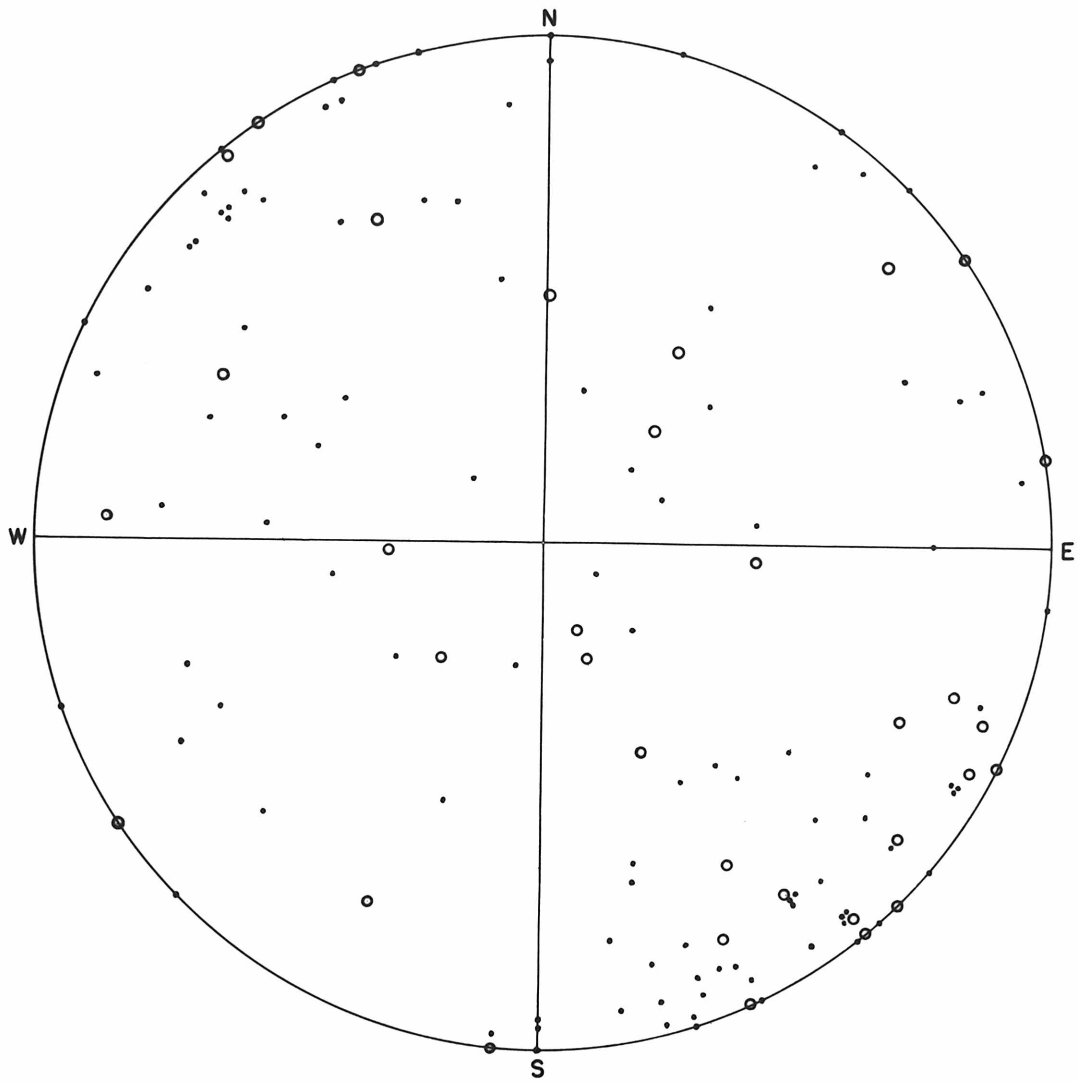


Figure 20 -- MODERATE JOINTS

Point diagram, showing poles of perpendiculars to 136 moderate joints. Plotted on upper hemisphere. Equal area projection.

- • Joints in Cerbat complex.
- ◦ Joints in Ithaca Peak porphyry.

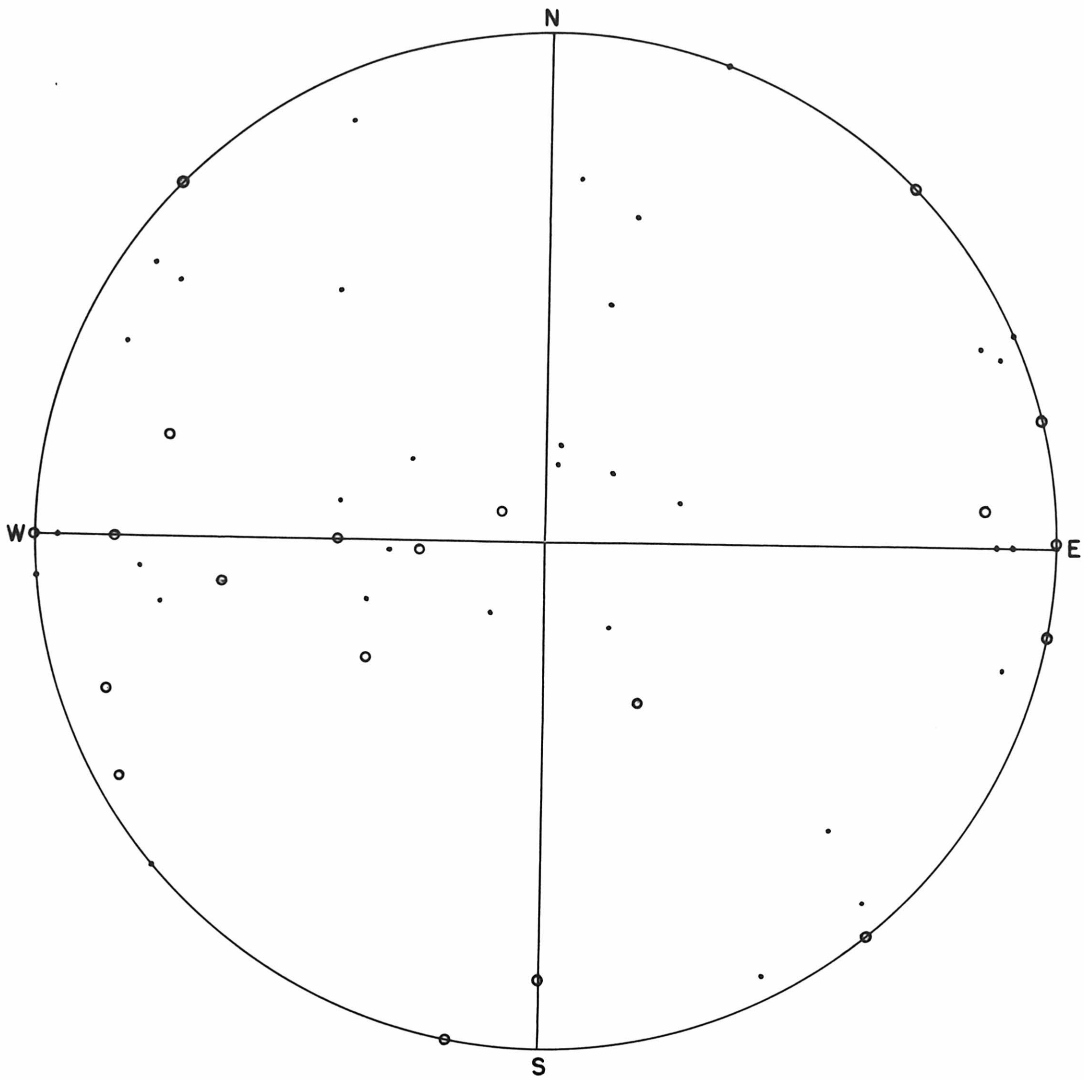


Figure 21 -- WEAK JOINTS

Point diagram, showing poles of perpendiculars to 54 weak joints. Plotted on upper hemisphere. Equal area projection.

- • Joints in Cerbat complex.
- ○ Joints in Ithaca Peak porphyry.

northwest-southeast. Under such a stress, the theoretical fracture planes that should develop in the rocks agree well with many of the observed joints. Tension fractures should form parallel to the direction of compression, and these are represented by the northwest trending, strongest set of joints. Shear fractures should be directed northeast and north, and many of the moderate and weak joints follow such trends. However, the wide variations in attitude shown by the moderate and weak joints emphasize the actual complexity of stress and strain conditions. The uniformity of the strong joints, on the other hand, suggests that they did originate as tension fractures due to compressional deformation.

The joint pattern was of major importance in later geological events. The fractures served as avenues of injection for numerous silicic and mafic dikes and were a prime factor in determining the location and orientation of the quartz-sulfide veins.

Ithaca Peak porphyry -- Joints in the Ithaca Peak porphyry sill and stock follow the same trends as those that cut the Cerbat complex. This fact is demonstrated in Figures 19, 20, and 21. Some of the joints must be genetically related to the intrusion and solidification of the magma. However, northwest-southeast compression, similar to the pre-Cambrian forces, established secondary foliation and is believed to be responsible for most of the joints. A joint belonging to the strong northwest trending set is shown in Figure 22.

FAULTS

The oldest recognizable faulting has left zones of mylonite in the Cerbat complex. The mylonite zones have been assigned a pre-Cambrian age, which may or may not be a valid assumption. They represent localized intense shearing parallel to the northeast structural trend of the Cerbat complex. One possible interpretation of these zones is that they were

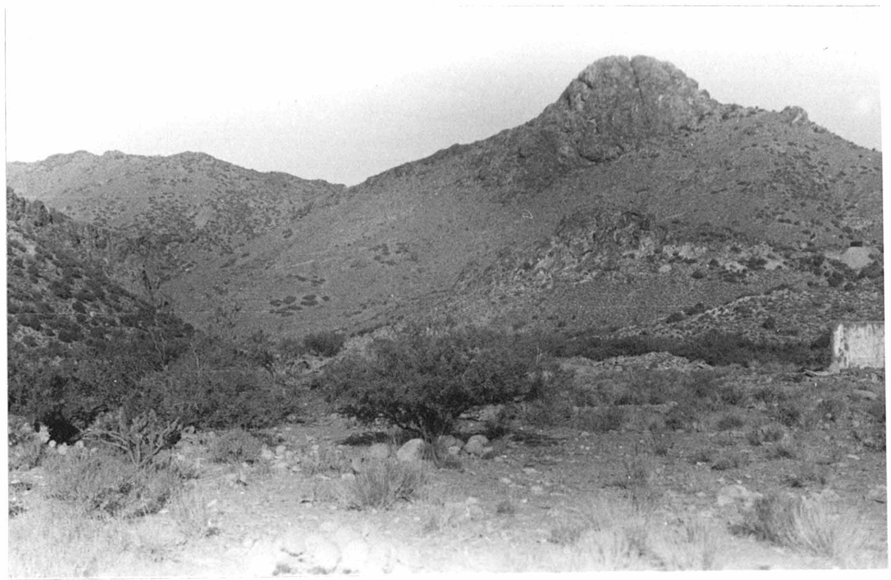


Figure 22 -- Nigger Head peak, Mineral Park district. Strong joint, striking NW and dipping steeply NE cuts center of peak. View looking NW.

formed along high-angle thrust planes.

Beginning with the intrusion of the Ithaca Peak porphyry, a number of ages of faulting is evident. Minor dislocations accompanied the periods of injection of granite porphyry dikes, lamprophyres, and rhyolite and andesite dikes. The maximum displacement for any of these was observed in the ridge northeast of the North Georgia mine. Here a vogesite dike offsets a diabase dike 100 feet horizontally. Dike injection and associated faulting followed the already established jointing trends in the Cerbat complex and the Ithaca Peak porphyry.

Mineralized Faults -- The most obvious faults are those along which veins have formed. Detailed mapping in the Chloride district has revealed a large number of veins. (See Plates 1 and 4), most of which occur in the eastern half of the district. In the latter area the veins have in general a northwest strike. The vein system is continuous to the south through the Mineral Park, Stockton Hill, and Cerbat districts and is fundamentally unchanged in pattern, as more than 80 percent of the observed veins strike west-northwest or northwest. In the central part of the Chloride distrcit the veins trend north, parallel with the intrusive contacts of the eastern limb of the Ithaca Peak porphyry sill. In the western part of the district the veins are less numerous and have no uniform trend. An east-west orientation is characteristic in the center of the Diana granite. Some of the veins intersect, and many are joined along the strike. Attitudes of all observed veins are shown in Figure 23. Comparison of this point diagram with the diagrams of the joints (See Figures 19, 20, and 21) demonstrates that relief of stress during vein formation occurred chiefly along the northwest trending set of strong fractures. This diagram also indicates the vertical to steep dips of most of the veins. Dips to the northeast are most numerous, but there

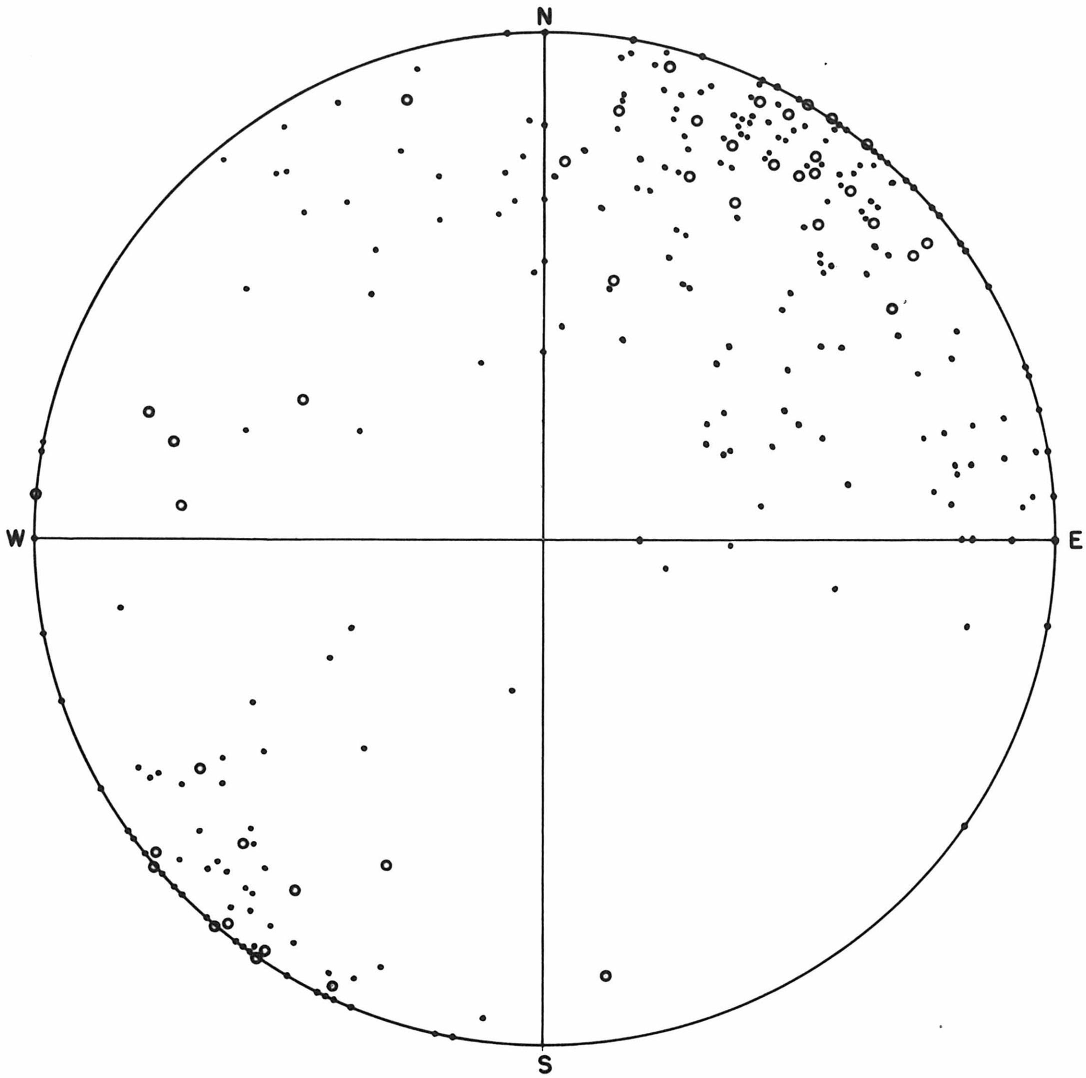


Figure 23 -- VEINS

Point diagram, showing poles of perpendiculars to 268 veins. Plotted on upper hemisphere. Equal area projection.

- • Veins in Chloride district.
- o Veins in Mineral Park, Cerbat, and Stockton Hill districts.

are many dips to the southwest. In the steeper veins reversals of dip are not uncommon.

Striations in the vein walls indicate that displacement has almost invariably been oblique. The prevalent slickensided surfaces, large amounts of gouge, and rolled and crushed fragments of wall rock show that shearing stress must have been important. Most are believed to be normal faults, though some seem definitely reverse. In steeply-dipping oblique-slip faults the distinction between normal and reverse movement has little significance, as a change in dip of a few degrees can easily result in a change in classification.

It is impossible to determine the amount of movement in most places. A few mineralized faults offset dikes of pegmatite and lamprophyre, however, and a horizontal displacement of 120 feet was measured along a vein that offsets a lamprophyre in the northwest corner of S 33, T 23 N, R 18 W. No markers were found to determine the amount of vertical movement.

Five periods of activity are reflected in the mineralized faults. The first was that which opened the fissures and gave access to mineralizing solutions. This was followed by three intra-mineral fracture periods and strong post-mineral fracturing.

The mineralized faults are younger than rhyolite and andesite dikes of Tertiary (?) age.

Transverse Faults -- Steeply-dipping, intra-mineral cross faults cut some of the veins and have produced small offsets. An example of this is in the Tennessee-Schuylkill mine where a fault striking N 50 degrees E and dipping 55 to 60 degrees N has offset the main vein a maximum of 30 feet horizontally.

A large post-mineral transverse fault cuts several veins in the eastern part of the Chloride district. It strikes N 55 degrees E, is essentially vertical, and can be traced for three-quarters of a mile. The north end of the Payroll vein is terminated against this fault. The North Georgia vein, on the opposite side of the fault, is similar in size and appearance and seems to be a continuation of the Payroll vein. This indicates a horizontal offset of about 500 feet, in which the north side of the fault was displaced to the west relative to the south side. The fault surface is exposed on the north side of the wash, one-quarter of a mile southwest of the Payroll mine shaft. In the fault exposure a one foot width of unmineralized gouge and breccia occurs.

Normal Faults -- Evidence of normal faulting is commonly present where remnants of volcanic strata occur. Four periods of faulting have been inferred from the relations of volcanic exposures. The earliest took place within the period of extrusion of the Bull Mountain andesitic series. A post-Bull Mountain series stage is suggested by the rhyolite which lies disconformably upon the Bull Mountain series, and a post-Kingman series stage is reflected in the tilting of rhyolitic strata along the west side of the range. A late stage is shown by the breaking and tilting of the Big Wash andesite. It is impossible to assign other than relative ages to the faulting, and the existence of the two middle periods may be open to question. Possibly these periods correspond to the four periods of basin-range faulting established by Sharp in the Ruby-East Humboldt range of northeastern Nevada 53/ and by Ferguson in the Hawthorne and Tonopah quadrangles of western Nevada 54/. The distribution and trend of these normal faults is shown in Figure 24.

East side of Cerbat Range -- The volcanic rocks in the Chloride quadrangle are most abundant along the east side of the range. Therefore most of the observed faults occur on that side, since the faults are only

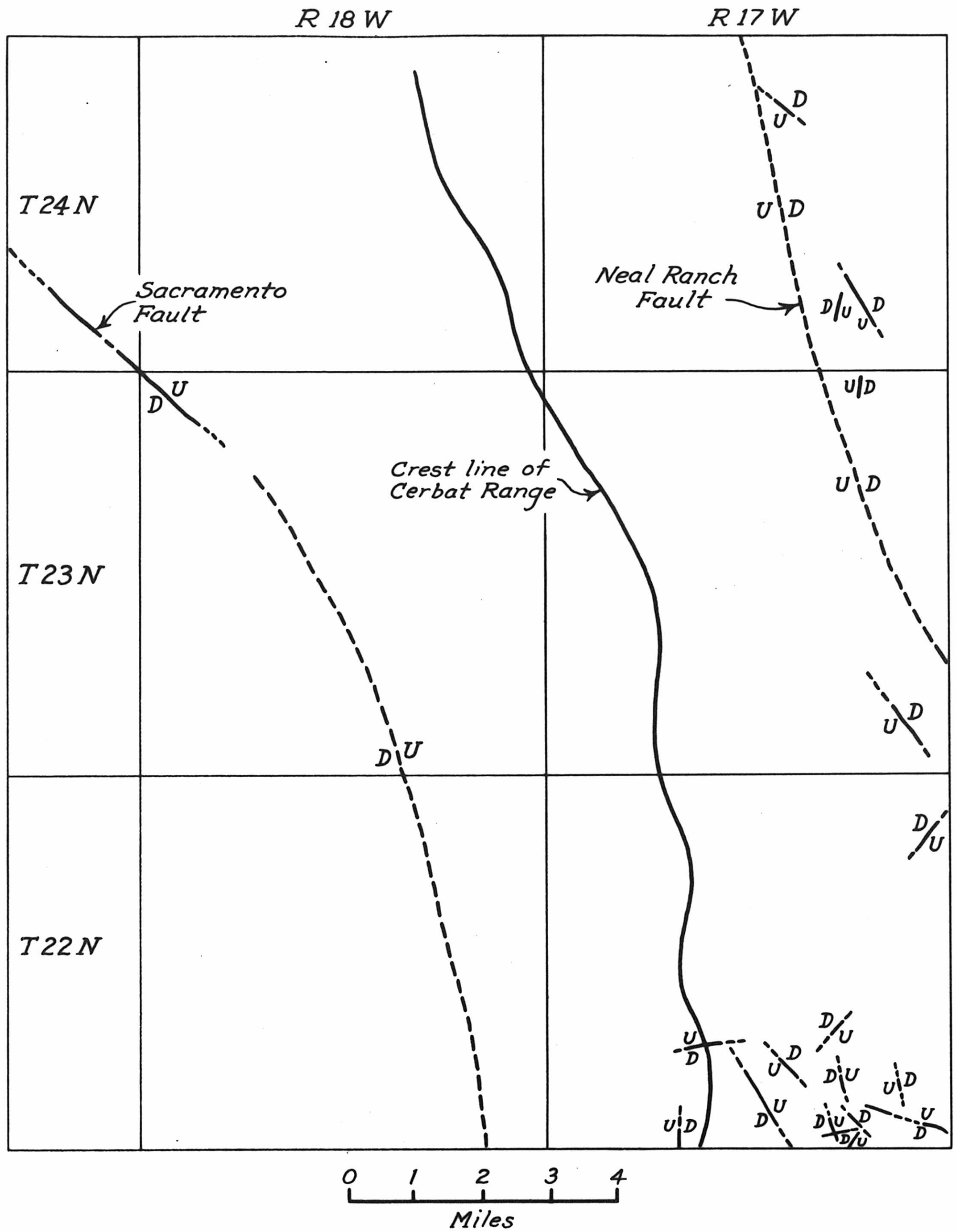


Figure 24 -- Trend and distribution of normal faults in the Chloride quadrangle. Inferred faults shown by dashed lines.

visible within the volcanics. They undoubtedly continue within the basement rocks, and similar faults probably exist outside the volcanic areas. Most of the faults strike north-northwest in echelon. The others trend northeast in echelon. The faults are steeply dipping, and dislocation seems to have been dip-slip. Total displacements could not be determined, but in many of the faults it probably was not more than a few hundred feet. The fault that passes just to the west of the volcanic-capped mesas north of Vock Wash, however, has displaced the volcanic cap rock a minimum of 700 feet vertically. The alignment of unusually straight canyons and ridge slopes, north and south of Vock Wash, suggests a length of ten miles for this fault. It passes just west of the Neal ranch buildings and is here termed the Neal ranch fault. It possibly continues and bounds the west side of the lava-capped mesa which is north of Neal ranch and outside the border of the quadrangle (See Figure 25). Most of the faults along the east side of the range, including the Neal ranch fault, are believed to be post-volcanic in age.

<u>West side of Cerbat Range</u> -- A large normal fault west of the Chloride district is revealed by the displacement of a series of volcanic strata. It seems to be a boundary fault for the Sacramento Valley and is therefore designated the Sacramento fault. It strikes N 48 degrees W and dips approximately 60 degrees S. From the point where it disappears beneath alluvium southwest of the district, it was mapped to the northwest for 2½ miles. The fault continues an unknown distance beyond the area mapped. In Figure ~~22~~ 24 the line of faulting is continued to the south by a dotted line. The position of this line was located just west of the pediment area along the front of the range. Faulting cannot be proved along this line, but the continuation of the Sacramento fault, or the existence of similar normal faults, is suggested by the truncation at

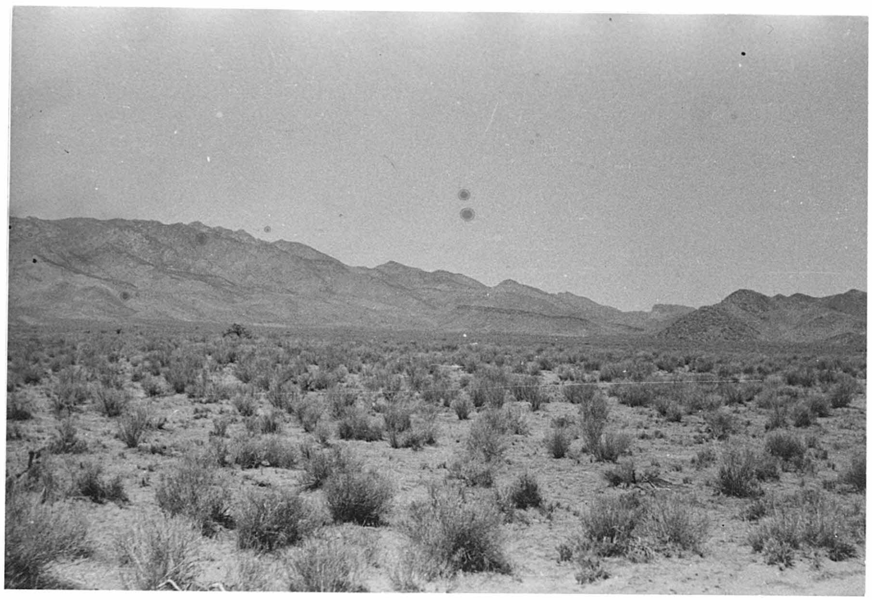


Figure 25 -- View north from Neal ranch. Lava capped fault-block in right center. Neal ranch fault on west side of mesa (?).

the mountain front of the internal structure of the range. The lack of outlying ridges and buttes further suggests that the faulting occurred along a single line or narrow zone, in contrast to the echelon pattern along the east side of the range.

The amount of displacement along the Sacramento fault cannot be determined accurately. A calculation of possible movement was made by using a 300-foot horizontal offset of the contact between the Ithaca Peak porphyry and the Cerbat complex. By neglecting any effects of ~~tear~~ auxiliary-faulting and assuming only dip-slip motion, a net vertical displacement of 3,165 feet and a net horizontal separation of 1,830 feet were obtained. That this may be approximately correct is indicated by the average relief of 3,000 feet in the northern part of the Cerbat Range.

Though the total displacement along the Sacramento fault must have taken place by intermittent movement, it seems to be one of the youngest geologic features in the region, for it was not in existence during the outpouring of Tertiary lavas. On the basis of the assumed Tertiary age of the rhyolites and andesites, the faulting probably started in late Tertiary and possibly extended into Quaternary time. Even late Quaternary activity is suggested by the eastward tilting and rejuvenation of the mountain block, which has caused the development of Recent gravel terraces. The most logical cause of such tilting would be vertical displacement along the Sacramento or other faults on the west side of the range. R. P. Sharp, summarizing studies of basin-range structure, states that "the period of maximum block-faulting in the Great Basin seems to have been latest Tertiary and Quaternary" <u>55/</u>. Evidence of block-faulting in the Cerbat Range is in accord with this generalization.

<u>Auxiliary Faults</u> -- Two auxiliary faults, which seem to be vertical, cut the hanging wall block of the Sacramento fault (See Plate 1) and join the Sacramento fault at angles of about 65 degrees. They bound a

segment of the Kingman rhyolite series and indicate that there has been breaking and differential movement of the hanging wall block of the Sacramento fault. The segment of rhyolitic strata has been dropped down relative to either side and is bounded on three sides by Ithaca Peak porphyry.

Relative downdropping between vertical auxiliary faults has also preserved narrow strips of basalt along the footwall side of the normal fault southeast of Neal ranch. No measurement of displacement was possible on any of these auxiliary faults.

Emerald Isle Fault -- Evidence of late normal faulting exists at the Emerald Isle mine in the Sacramento valley west of Mineral Park. Here both the bedrock pediment and the overlying blanket of alluvium have been faulted, and the fissure has been mineralized by copper-bearing solutions. The fault strikes N 30 degrees E and dips between vertical and 45 degrees. The fissure vein in the gravels is as much as 12 feet wide and has distinct walls. The amount of displacement was not determined, but the occurrence of bedrock in the footwall, next to gravel in the hanging wall, indicates a normal fault.

Present form of the Cerbat Range -- The delineation and uplift of the present mountains has been a consequence of large normal fault activity. Maximum dislocation occurred along the west side of the range, resulting in an eastward-tilted block. In the northern half of the quadrangle, however, between the Sacramento and Neal ranch faults, the range is an eastward-tilted horst. The structural grain of the basement rocks, which trends northeast, is truncated almost at right angles by these normal faults. Differential vertical stresses must have been of major importance, in contrast to the compressive forces that characterized the earlier history of the region.

GEOLOGIC HISTORY

The nature and sequence of events in pre-Cambrian time have been discussed. The following is a summary of the later geologic events that have been recorded in the area studied.

Following the pre-Cambrian, a large gap occurs in the geologic record. Several thousand feet of Cambrian, Mississippian, and Pennsylvanian sediments overlie the basement crystalline complex in the Grand Wash Cliffs, only 12 to 15 miles east of the Chloride quadrangle. In the Cerbat Range similar strata are totally lacking. With large thicknesses of Paleozoic rocks so close at hand, their former extension over the Cerbat complex would be expected. They might have been much thinner, though, as the Chloride quadrangle is on the northeast edge of Schuchert's "Ensenada", a Paleozoic land area or positive element 56/. If Paleozoic sediments were formerly present, removal has been thorough. Schrader mentions limestone from a well northwest of Kingman which he thought might be Paleozoic 57/. Nothing of similar nature has since been recorded.

There are no features that can be related definitely to the Mesozoic. If the region received Mesozoic sediments they have been removed. The Laramide revolution is reflected in the Muddy and Virgin Mts., in the region to the north of the Chloride quadrangle 58/. It may have affected the Chloride quadrangle, and features such as secondary foliation and mylonitic zones in the Cerbat complex might be due to late Cretaceous or early Tertiary compressive forces. Furthermore, the Diana granite could be of Laramide age. It is felt that these features fit better into the pre-Cambrian sequence, and they have been so classed, but it is readily admitted that the classification is arbitrary. As a matter of fact there is nothing, aside from alluvium and its associated sheets of olivine basalt, that can be dated with any degree of assurance.

Specific ages can be assigned only with a question mark.

Intrusion of Ithaca Peak porphyry and related rocks -- In the Tertiary (?), the Ithaca Peak granite porphyry intruded the Chloride and Mineral Park districts. These bodies were guided in their emplacement by pre-existing structure. They were accompanied by the profuse injection of granite porphyry dikes, especially in the Chloride district. Northwest-southeast compressive forces, in operation possibly during and definitely after emplacement and consolidation of the granite porphyry, produced different degrees of secondary foliation in the intrusions.

Minor amounts of pegmatite and aplite are associated with the Ithaca Peak porphyry, and lamprophyre dikes are common, apparently derived by differentiation of the granite porphyry magma at depth. A feature of all the dikes, including the granite porphyry dikes, is their occurrence in composite bodies. Many old fracture lines, previously invaded by pegmatite and diabase, were successively re-opened to granite porphyry and lamprophyres, and in some places to rhyolite and to vein-forming solutions.

Volcanic period -- This entire region probably once was covered by a great thickness of pyroclastic volcanic debris and lava flows of Tertiary (?) age. Andesitic flows, tuffs, and breccias of the Bull Mountain series represent the first stage of volcanism. A period of normal faulting and erosion occurred between the eruption of the lower and upper beds, and erosion and probable normal faulting followed the accumulation of the series. Succeeding volcanism came from silicic magma, and the Kingman series of rhyolite flows, tuffs, and breccias was deposited disconformably upon the lower andesites. Tilting of the rhyolites, probably due to faulting, and truncation by erosion took place on the west side of the range but is not indicated on the east side. A later eruption unconformably capped the Kingman rhyolite with the Big Wash andesite, to end the general period of volcanism. Numerous rhyolite and a few andesite dikes of Tertiary (?) age cut the basement rocks.

Sulfide mineralization -- Sulfide mineralization occurred after the injection of the rhyolite and andesite dikes. The first period of mineralization was localized almost entirely within the Mineral Park stock of Ithaca Peak porphyry. A large part of the stock was broken into closely-spaced fractures which were utilized by hydrothermal mineral solutions. The result was a low-grade disseminated sulfide deposit.

After an interval of unknown length a second and more extensive period of mineralization occurred. The solutions followed fissures, most of which were localized along northwest trending old fractures. The result was a system of quartz veins that contain sulfide ore minerals. Veins of this period cut across the disseminated sulfide deposit and are the only ore deposits of the Chloride, Cerbat, and Stockton Hill districts.

Basin-range faulting -- After the conclusion of volcanic activity, and presumably in the late Tertiary, the present mountains began to form. The Sacramento normal fault, or fault system, was formed and the east side of the fault was progressively elevated relative to the west side. A total vertical displacement of several thousand feet was eventually reached. The rising mountain block was also tilted so that it sloped 5 to 10 degrees to the east. Contemporaneous with activity along the Sacramento fault, normal faults in echelon, most of them striking northwest, disrupted the rocks along the east side of the block. Vertical displacements were not as large as on the Sacramento fault, but the Neal ranch fault had significant dip slip movement and established a tilted horst structure for part of the mountains.

Large quantities of erosional debris were shed from the rising block, and a broad pediment was cut along the base of the range. At a late stage, alluvium had begun to choke the canyons draining the mountains. The western side of the block was then elevated once again, and the streams are now down-cutting, having left terraces up to 50 feet above their present grades. This rejuvenation is believed to stem from late Quaternary movement along the Sacramento or related faults.

Emerald Isle mineralization -- In late Quaternary time, after the bulk of the alluvial fill had accumulated in the Sacramento valley, and after cutting of the pediment, another period of mineralization occurred. Mineralizing solutions ascended along a northeast-striking normal fault fissure, which extended out of bedrock into alluvium at the site of the present Emerald Isle mine. Chrysocolla and other copper silicate minerals were deposited both in the fault fissure and in the surrounding alluvium. This mineralization must be later than the main period of active movement along the faults bounding the range. It may be earlier than the last rejuvenation, however.

Relations between basin-range faulting and sulfide mineralization -- Both basin-range faulting and sulfide mineralization seem to have taken place after the conclusion of Tertiary volcanic activity. The question of their relative ages, within the post-volcanic period, immediately arises. If late rejuvenation along the west side of the range indicates boundary fault movement, it is safe to say that basin-range faulting has been active after completion of sulfide mineralization. This is shown by veins which were truncated by erosion at the pediment surface, buried under a blanket of alluvium, and later exposed by down-cutting that is a function of this rejuvenation.

There are no traces of mineralization along the Sacramento fault. It therefore might be assumed that the fault is completely post-mineral, especially as it passes within 2500 feet of strong veins. But the assumption has little weight, as the amount of gouge that might form along a fault of this size could effectively seal it against hydrothermal solutions.

If mineralogical and textural differences could be demonstrated between veins in the pediment and those several thousand feet higher, near the crest line of the mountains, it might indicate that the mountains were elevated after vein formation was complete. If that were true the deeply eroded veins at the foot of the range should have features of greater depth of sulfide mineral formation. The veins, however, are the same from mountain top to pediment. Zoning does not seem to occur in these veins, and the opposing argument, that the veins were formed after the sculpturing of the mountains, likewise has no support.

The only conclusion is that sulfide mineralization was prior to or contemporaneous with basin-range faulting.

Extrusion of olivine basalt -- The last geological event, apparently of Recent age, was the extrusion of sheets of olivine basalt. These overlie and interfinger with alluvium, and in one place basalt seems to lie across the Sacramento fault.

ORE DEPOSITS

VEIN DEPOSITS

INTRODUCTION

Ore was discovered in the Cerbat Mountains in 1863, and the name Sacramento district was applied to the area. Early production was small, work was hazardous, and the prospectors were soon driven out by the Hualpais Indians. A party re-entered the area in 1871 after the Indians were subdued, many new veins were discovered, and the term Hualapais district came into general usage. A large influx of miners from Nevada and California took place in 1872. The near-surface oxide ores, which were exploited for gold and silver in the early days of mining, were apparently extremely rich. Schrader says that large profits were realized, though most of the ore, prior to the advent of the railroad in 1882, was packed by burros "to the Colorado River, thence by river steamer to Port Isabel, down the gulf to Point Arena, and up the coast to San Francisco, whence they were shipped to England for treatment" 59/. In addition to this complicated shipping route, some ore was treated in arrastres, probably for the most part by Mexican miners who brought the process with them across the border. This technique consisted of attaching heavy slabs of rock by chains to the ends of a long beam projecting from an upright spindle. The spindle and beam were revolved by burro-power, dragging the slabs around in a circular pit, surfaced and edged with flat stones. The ore was thrown into the pit with water and quicksilver, ground by the revolving slabs, and the precious metals recovered as amalgam. Remains of these old arrastres occur throughout the area. A well preserved pit is shown in Figure 26.

A small custom mill was erected at Mineral Park in the later seventies but did not greatly stimulate production. Perhaps one reason was that

Figure 26 -- Mexican arrastre in canyon bottom immediately southeast of Kay ranch house.

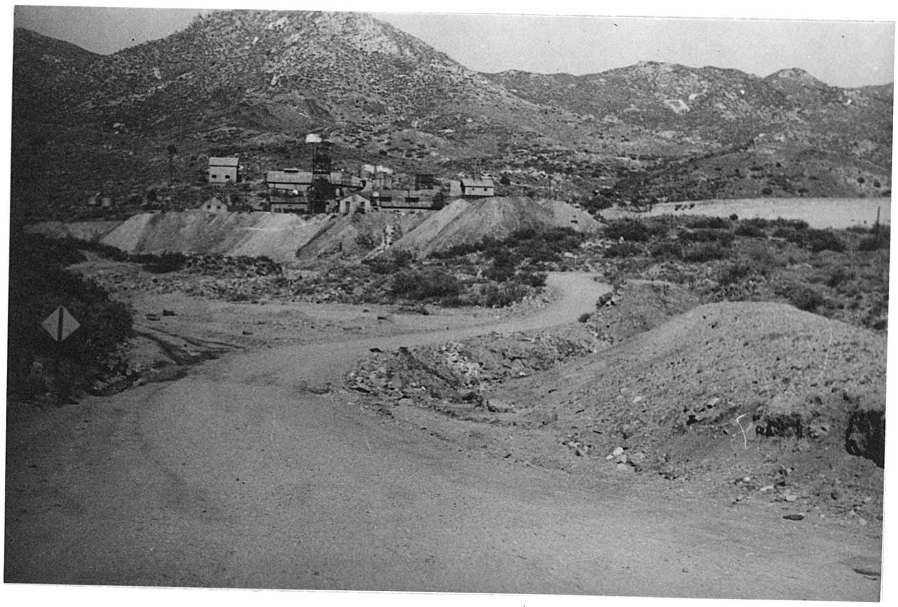


Figure 27 -- Buildings and dumps of Tennessee-Schuylkill mine. View looking east.

the miners were paid by checks, which were discounted for cash by 20 percent.

Only after the advent of the railway in 1882 was the first development work below water level done. However, the depreciation of silver and the encountering of lower grade sulfide ores at depth combined to cause a slump in mining in the 1890's and early 1900's. A rise in the price of base metals caused a revival in 1906, and the period from 1906 to 1912 saw the greatest sustained activity in the history of the region, with production coming principally from sulfide ores. Since that time the main productive periods have coincided with base metal demand provided by the first World War and World War II.

Only two mines have large production records, the Golconda in the Cerbat district and the Tennessee-Schuylkill in the Chloride district. The Golconda is credited with a gross production of $6,500,000 60/ up to 1917. The mill was destroyed by fire in that year, and the property has not produced since. The mine was developed to a depth of 1600 feet, and at one time it was the largest zinc producer in the state of Arizona. The Tennessee-Schuylkill produced a small amount of ore during the early nineties, operated steadily from 1910 to 1916, operated intermittently from 1917 to 1936, and has been producing more or less continuously from 1936 to the present. It has been developed to a depth of 1400 feet, has winzes to 1600 feet, and has yielded about 300,000 tons of ore averaging 4.33 percent lead and 7.74 percent zinc, and containing appreciable gold and silver 61/.

Hernon gives the following production figures for the Cerbat Range for the years prior to and including 1930 62/:

Copper (lb)	Zinc (lb)	Lead (lb)	Gold	Silver	Total
2,900,000	95,587,344	55,350,000	$2,339,000	$5,038,000	$20,270,000

The total volume of ore from 1908 through 1933 was 615,514 tons, valued at $13,360,978 63/. The production for the years 1934 to 1946 inclusive was 703,701 tons, with a total value of $9,508,187 64/. Considering the many years of early operation, from which no production statistics are available, the total value of ore gained from the Cerbat Range is probably close to $35,000,000.

An indication of the average grade of present ores is given by the milling records of 20,222.5 tons of custom ore that were treated by the Mineral Park Milling Co., from 1945 to 1947 inclusive. The average assay figures on this ore are 0.058 ounces of gold, 3.56 ounces of silver, 0.404 percent copper, 3.30 percent lead, and 5.67 percent zinc 65/.

DISTRIBUTION OF VEINS

The general limits of the area within which sulfide-containing fissure veins occur are shown in Figure 28. It can be seen that the mineralization occupies an elongate zone or belt. This belt strikes approximately N 35 degrees W, and is 4 to 5½ miles wide by 14 miles long. Centrally located within the belt is an area of "porphyry copper" mineralization. From south to north, in the Cerbat, Stockton Hill, and Mineral Park districts, and in the eastern portion of the Chloride district, most of the veins strike about northwest. This distributes the veins in echelon within the belt of mineralization. The prevailing trend is demonstrated in the point diagram of Figure 23.

The greatest concentration of veins occurs in the roughly triangular section between the east limb of the Ithaca Peak porphyry sill, in the Chloride district, and the north side of the Mineral Park stock. Here more than 100 veins are present in an area of not more than 6 square miles. (See Plates 1 and 4). The veins in this area follow the prevailing trend. In the balance of the Chloride district the veins deviate

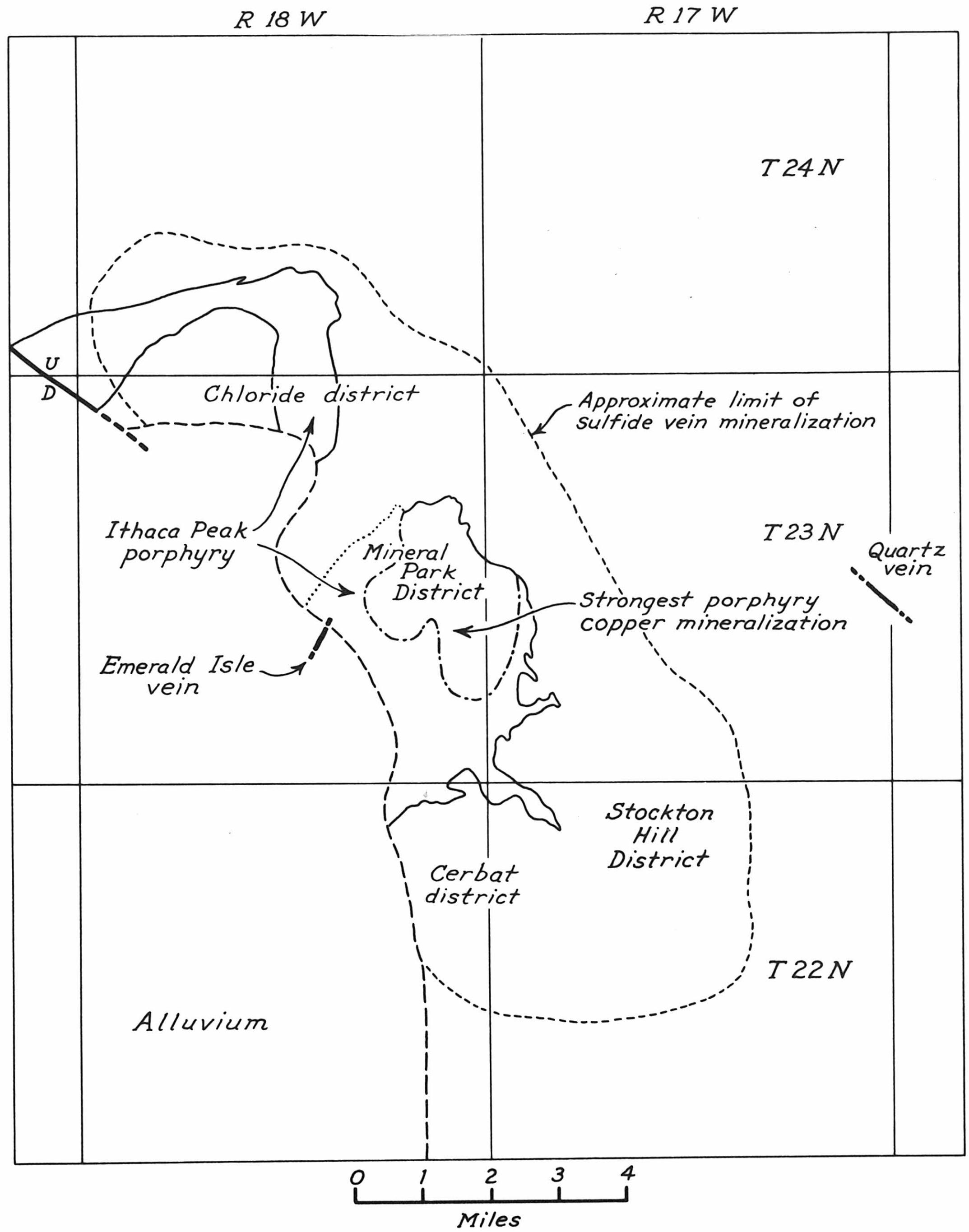


Figure 28 -- Generalized diagram of distribution of mineralization in the Chloride quadrangle. Note central location of porphyry copper mineralization and symmetrical pattern of superimposed fissure vein mineralization.

radically from this trend and strike in many directions. Plate 1 shows that the arrangement is not haphazard, however, but reflects an anticlinal pattern in the rocks. This is most obvious in veins that are parallel to the intrusive contacts of the Ithaca Peak porphyry sill.

PRIMARY MINERALS

The following primary minerals have been identified in the vein deposits:

Gangue Minerals

Quartz . . . . . SiO_2 --- Most abundant; present in all veins.

Calcite . . . . $CaCO_3$ -- Present in many veins.

Manganocalcite . $(Ca,Mn)CO_3$ -- De La Fontaine mine.

Siderite . . . . $FeCO_3$ -- Minor, but widespread.

Fluorite . . . . CaF_2 --- Chloride district; in 2 veins.

Ore Minerals

Pyrite	FeS_2	
Marcasite (?). .	FeS_2	
Arsenopyrite . .	$FeAsS$	Common assemblage of mineral belt.
Sphalerite . . .	ZnS	
Galena	PbS	
Chalcopyrite . .	$CuFeS_2$	

Tetrahedrite . .	$5Cu_2S.2(Cu,Fe)S.2Sb_2S_3$	Very rare.
Tennantite . . .	$5Cu_2S.2(Cu,Fe)S.2As_2S_3$	

Proustite . . . $3Ag_2S.As_2S_3$ -- Most abundant silver mineral; rare in present ores.

Pyrargyrite . .	$3Ag_2S.Sb_2S_3$	
Polybasite . . .	$9Ag_2S.Sb_2S_3$	Minor amounts, with proustite.
Miargyrite . . .	$Ag_2S.Sb_2S_3$	

Gold . . . . Au -- Present in minor amounts in all ores.

Bastin has recorded, also, the occurrence of pearceite ($9Ag_2S.As_2S_3$), argentite (Ag_2S), and manganiferous siderite, $(Fe,Mn)CO_3$ as primary ore minerals 66/.

PARAGENESIS OF THE ORES

The following discussion is based on an examination of sixty-four polished sections. Most of the specimens were taken from mines, ore-bins, and dumps throughout the Chloride district. Others were taken at scattered locations in the balance of the mineralized belt. The results of the examination give a composite picture of the history of mineralization. The stages in this history that are found in any single mine or prospect have been dependent upon the local maintenance of fissures and openings and upon the variable physico-chemical conditions affecting the solutions. The paragenetic relations are summarized in Figure 29.

Age Criteria -- Prior to detailing the paragenetic relationships of the ore minerals, mention should be made of the criteria that were used in determining age diversity or similarity. Of the many criteria that have been suggested 67/, only a few were felt to be sufficiently diagnostic to be relied upon. Depositional features in vugs and fractures, and cross-cutting veinlets, were used with confidence in determining successive deposition of minerals in any one section. Crustification banding was also used, with the realization in mind that any single mineral layer might represent more than one stage of deposition. Such a condition is possible, as later replacement could add appreciably to an initial layer. Crystal outlines were used in places as indicative of mineral succession. As discussed by Bastin 68/, this involves the assumption that where crystal boundaries of a grain are convex outward the grain is older than the surrounding mineral. Conversely, cancave crystal boundaries outward would indicate that the surrounding mineral is the older. This cannot be used haphazardly, however. Force of crystallization must always be considered,for example euhedral pyrite may develop either simultaneously with or later than surrounding quartz, and the application of this crystal outline principal would give an invalid result. It is most useful where supplemented by pitting, corrosion, or other replacement phenomena.

The only replacement features used with confidence were veinlets with non-matching walls, where attack on the older minerals was reasonably clear. Supplementary evidence, which was sometimes useful, included "island to island" and island to mainland" relationships. In this, isolated inclusions are assumed to be older than the surrounding mineral where they show parallel orientation with each other and with a nearby parent mass. Of confirmatory value was the form of host-guest contacts, where boundaries smoothly concave toward one mineral may indicate that it is the guest. Care must be taken not to confuse this replacement "caries" type contact with crystal outlines, where concavity toward a mineral holds an opposite age connotation.

It was virtually impossible to make direct determinations of simultaneous deposition. Perhaps the most reliable criterion is the occurrence of two or more minerals as adjacent segments of a veinlet filling, though this condition could also result from replacement. The lack of data showing age diversity might be taken to indicate simultaneity, but the method is inherently weak. It is strengthened somewhat by the not uncommon appearance of features of successive deposition or replacement between two minerals, which, in another portion of the same polished section will display reversed relationships. This could mean that both minerals were available in the mineralizing solutions at the same time, providing separate stages are not indicated elsewhere.

As implied in the above use of the terms supplementary and confirmatory, no single criterion should be taken as diagnostic of a condition. Where several can be applied, however, the accuracy of determination is improved. By examining a large suite of polished sections, enough mutually supporting evidence should be fouhd to give a consistent picture of paragenetic relations. The conditions displayed in any one polished section may be incomplete, but through the study of many sections a composite history of mineralization can be compiled.

Introduction of quartz -- Newly established fissures and re-opened old fracture systems were first occupied by quartz. Pressure conditions were apparently low enough so that self-sustained openings were maintained. As a result, the rising solutions typically deposited euhedral crystals of clear to milky-white quartz. The formation of "comb crystals" lining the walls of open fissures was common. Quartz continued to be deposited intermittently throughout the period of vein formation.

Introduction of pyrite and arsenopyrite -- Pyrite and arsenopyrite were introduced after the first quartz began to be deposited. They typically developed crystal forms, and euhedral to subhedral intergrowths of early quartz, pyrite, and arsenopyrite are common. The evidence for the earlier time of introduction of the quartz is displayed in specimens where early quartz crystals, lining fissure walls, have been surrounded by pyrite and arsenopyrite, and the crystal faces of the quartz have been corroded and replaced.

No conclusive evidence was seen that would establish priority of introduction for either pyrite or arsenopyrite. One or both may occur in any single specimen, though pyrite is more abundant regionally. Pyrite would be expected to form first, on the basis of the usual sequence of hypogene ore minerals 69/. In many places pyrite is earlier, and is replaced by arsenopyrite, but in other places the relations are reversed. The two minerals seem to be essentially contemporaneous. The bulk of the pyrite and arsenopyrite was deposited in this early stage, prior to the introduction of the rest of the minerals. Small amounts recur in later stages, however.

Marcasite (?) -- In some specimens marcasite(?) and arsenopyrite occur as a very fine-grained mixture. Marcasite(?) was differentiated on the basis of polarization colors that differ from and are more vivid than those of arsenopyrite. The material seems to be contemporaneous with the arsenopyrite.

First intra-mineral fracturing -- Mild and local fracturing, dating after the introduction of arsenopyrite and pyrite, is present in a few specimens. It is shown by the presence of sphalerite as fracture fillings in the pyrite and arsenopyrite.

Introduction of sphalerite -- After the major period of deposition of pyrite and arsenopyrite, zinc was added to the solutions, and sphalerite began to deposit. Its relative age is established by veining, and by its position surrounding crystals of early quartz, pyrite, and arsenopyrite. Most of the sphalerite is brownish black to grayish black but some is light brown. No distinction in relative ages can be made between these two types, and the variation can be explained best by the assumption of local differences in the nature of the zinc-containing solutions, notably in the amount of iron that was present.

Inclusions of chalcopyrite are abundant in the sphalerite. These vary from microscopic specks to blebs that can be seen with the naked eye. There is no uniformity in the orientation of the blebs. None of the chalcopyrite resembles a crystallographic intergrowth, though straight lines of inclusions, possibly formed along cleavage planes, are not uncommon. More often the inclusions are scattered at random or seem to outline invisible grain boundaries. Furthermore, chalcopyrite veins sphalerite, occurs outside of sphalerite, and also replaces it. According to the criteria listed by Schwartz 70/, these features are not indicative of exsolution, and the presence of the chalcopyrite is therefore attributed to the effects of replacement along sub-microscopic openings in the sphalerite.

Second intra-mineral fracturing -- After the deposition of a considerable amount of sphalerite, many specimens show a second period of fracturing. Evidence of it is not abundant, but the fracturing is a little more widespread than was that of the first period. Veining by galena established its relative age.

Introduction of galena -- In some specimens galena follows sphalerite in order of introduction, for galena veins, corrodes, and rounds crystals of early sphalerite. In many specimens, however, the two minerals seem to be contemporaneous. Reversals of paragenetic relations are common, and in bulk both are best classed as "intermediate age" minerals. Both recur in small amounts associated with later minerals.

Third intra-mineral fracturing -- Some specimens display moderate fracturing that occurred after the deposition of both sphalerite and galena was largely complete. The fracturing is shown by cross-cutting veinlets occupied by later minerals, and by brecciated vein material which has been cemented by late quartz.

Introduction of chalcopyrite -- Blebs of chalcopyrite in sphalerite are interpreted as replacement features. Chalcopyrite occurs as replacement grains along boundaries of sphalerite and galena, and in veinlets cutting these and earlier minerals. Its time of introduction is believed to be later than the time of introduction of galena. This is based on the veining and replacement of galena by chalcopyrite and the lack of recognizable reverse relations. The chalcopyrite is only present in minor amounts and in small grains, however, and replacement features of chalcopyrite by galena might be present but not identifiable as such. Chalcopyrite occurs contemporaneously with all later minerals.

Introduction of latest minerals -- A varied assemblage of minerals was deposited during the last stage of mineralization. These minerals are minor in amount, and, aside from gold, are lacking in the majority of specimens. Minor variations in the paragenetic relations of these minerals exist between specimens, but on the whole they seem to have been introduced at about the same time, after the bulk of sphalerite and galena had been deposited.

Tetrahedrite and tennantite -- Tetrahedrite and tennantite are very rare and were only observed as microscopic grains. Tetrahedrite was seen in a specimen from the Mineral Park district and in a specimen from the Optimo mine. What may be tennantite occurs in a specimen from the Lucky Baldwin prospect. The two minerals are contemporaneous with silver minerals in tiny veinlets and cavity fillings.

Complex silver minerals -- The most abundant silver mineral is proustite, and it was observed in only a few specimens. Accompanying it in some specimens are minor amounts of pyrargyrite, polybasite, or miargyrite. The relative age of these minerals is established by their presence in veinlets cutting across galena and chalcopyrite.

These complex sulfides are believed to be primary. The best evidence of this is that quartz, galena, chalcopyrite, and ruby silver occur as segments filling the same veinlet. This is indicative of simultaneous deposition, and if the galena and chalcopyrite are primary the ruby silver must be primary. Bastin's detailed study in 1913 14/, at a time when specimens of the silver sulfides were more abundant, gives many other criteria which also suggest that the silver sulfides are primary.

Gold -- Gold, which invariably is recovered in small amounts from the primary ores, has not been detected, either in hand specimen or under the microscope, and its paragenetic position is unknown.

Calcite -- Calcite is the most abundant of the late minerals. It is present in many veins and in some places constitutes a large part of the gangue. Calcite is commonly present in specimens that show the late period of intra-mineral fracturing, and it fills veinlets that transgress galena and spalerite. The calcite, which is milky-white to colorless, is common as crusts of euhedral crystals.

Manganocalcite -- White to pale pink manganocalcite forms the gangue of a specimen from the De La Fontaine mine. The refractive indices were determined as N_e = 1.534 and N_o = 1.7 plus, which indicates a content of approximately 42 percent $MnCO_3$ 71/. It veins galena in several places and is possibly the same age as calcite.

Siderite -- Siderite was observed in only a few specimens but from such widely scattered locations as the New London mine, in the Cerbat district, and the Lucky Baldwin prospect, in the Chloride district. It was probably introduced at the same time as calcite for it veins galena and sphalerite. It ranges from light brown to grayish black in color.

Fluorite -- Fluorite occurs in at least two veins. Specimens collected from the dump of the Altata mine contain small clusters of colorless to light gray cubic crystals one-sixteenth inch or less in size. These crystals are set in a matrix of black oxide material, and none is in contact with the hypogene sulfides. In a specimenfrom the

Tintic mine a small band of colorless fluorite is superimposed upon a layer of quartz. This fluorite likewise does not occur in contact with any sulfides, and its paragenetic position cannot be determined.

Stibnite -- Stibnite occurs in the Chloride district, but no economic amounts have been discovered. The known deposits consist of a few small pockets located within a granite porphyry dike. This dike is exposed about 600 yards northeast of the Hercules mine and runs parallel with the Badger-Hercules veins in a west-northwest direction. A distinct vein is lacking, but the prospect holes have a linear disposition along the length of the dike and the granite porphyry is hydrothermally altered.

Examination under the microscope reveals that the granite porphyry first was subjected to mild fracturing that established small openings. These were utilized by mineralizing solutions which first deposited quartz, typically in small euhedral crystals. Stibnite followed, and it surrounds and corrodes small comb quartz crystals. Later quartz occurs in veinlets cutting the stibnite. No other sulfides were observed in the deposits, which prevents any satisfactory dating or placing of the stibnite in the regional paragenesis. There is the possibility, of course, that the stibnite represents a different period of mineralization.

Post-mineral fracturing -- In many specimens post-mineral movement is evident. In some places thorough brecciation has been accomplished. The lack of any primary mineral filling in the fractures indicates the post-mineral age. The effects are well demonstrated in specimens from the Payroll mine dump. In these complete brecciation took place, resulting in angular fragments averaging less than half an inch in size. The fragments have been tightly cemented by iron oxide.

Summary -- Emphasis has been placed on the time of introduction of the various minerals, for regionally the sequence is uniform. The period of deposition of any particular mineral, however, cannot be generalized easily. Perhaps the best summary statement is that quartz was deposited intermittently through the period of mineralization, the bulk of the pyrite and arsenopyrite preceded sphalerite and galena, and the bulk of the latter two minerals preceded the latest minerals. Deposition at any particular time and place was a function of such variable factors as temperature, pressure, concentration, rate of solution ascent, and permeable openings. As a result, the mineral relations in some specimens differ from those in other specimens, but all are contained within this general paragenetic pattern.

PARAGENESIS OF HYPOGENE MINERALS

(Vertical lines represent periods of fracturing)

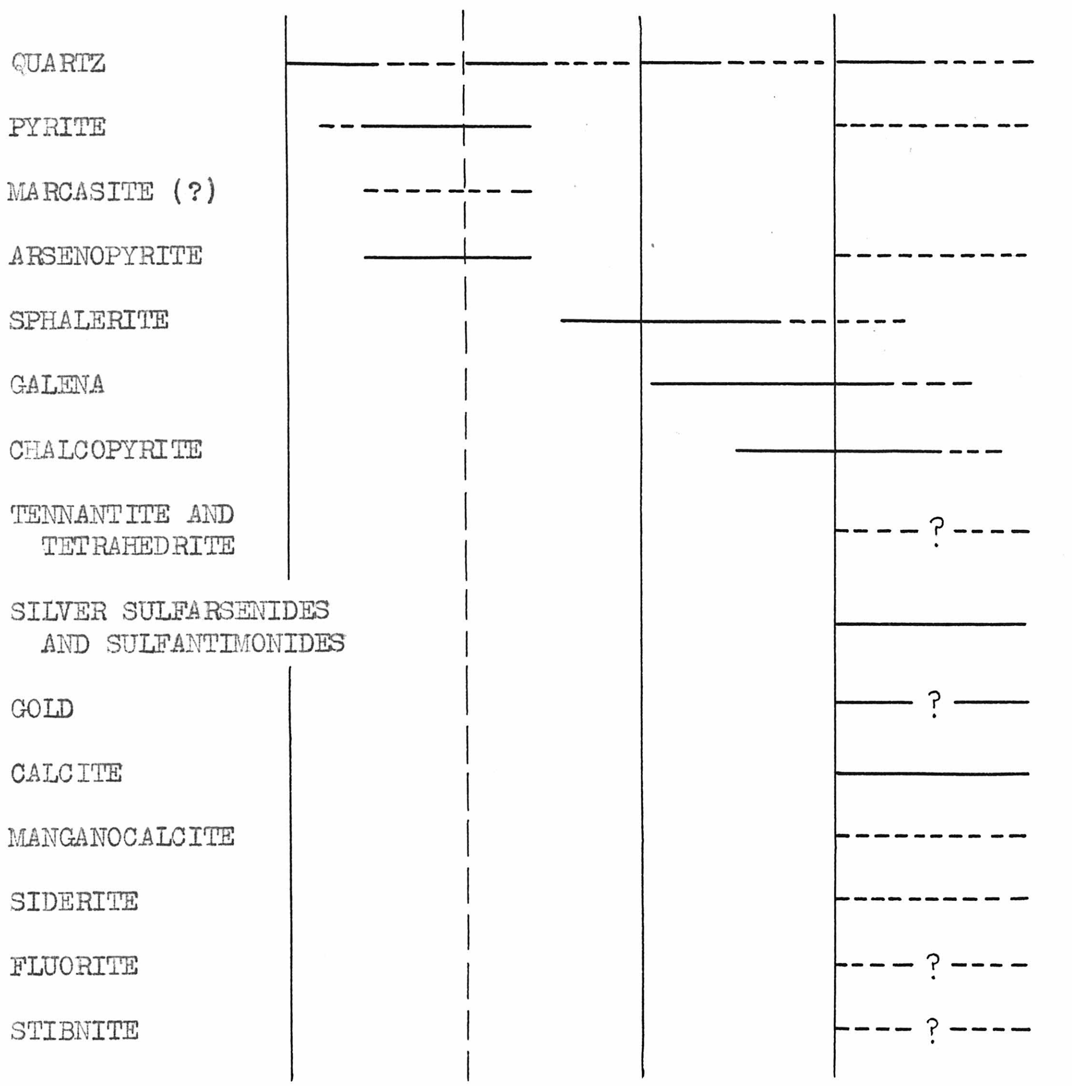


Figure 29 -- Paragenesis of vein deposits. Horizontal spacing is accommodated to the paper and indicates relative positions of minerals, not time units. Dashed lines indicate minor significance.

SUPERGENE MINERALS

The following minerals have been determined from the oxide zone of the vein deposits:

"Limonite" . . .	Fine-grained isotropic oxides of iron; very abundant.	
Goethite	$Fe_2O_3 \cdot H_2O$	
Jarosite	$K_2O \cdot 3Fe_2O_3 \cdot 4SO_3 \cdot 6H_2O$	Present in limonite.
Plumbojarosite .	$PbO \cdot 3Fe_2O_3 \cdot 4SO_3 \cdot 6H_2O$	
Limonitic jasper	------------------------	Common
Hematite	Fe_2O_3 ----------------	Accompanies limonite in places.
Chalcanthite . .	$CuSO_4 \cdot 5H_2O$	Mine walls.
Iron-copper chalcanthite . .	$(Fe,Cu)SO_4 \cdot 5H_2O$	
Anglesite . . .	$PbSO_4$	
Cerussite . . .	$PbCO_3$	
Covellite . . .	CuS ----------------	Common
Scorodite . . .	$FeAsO_4 \cdot 2H_2O$	
Mimetite	$Pb_5ClAs_3O_{12}$	
Chalcocite . . .	Cu_2S	
Cuprite	Cu_2O	
Native copper .	Cu	
Malachite . . .	$2CuO \cdot CO_2 \cdot H_2O$ --------------	Rare
Azurite	$3CuO \cdot CO_2 \cdot H_2O$	
Zinc carbonates		
Native silver .	Ag	
Ferrous arsenate(?)	--------------	Coatings
Manganese oxides		
Gypsum	$CaSO_4 \cdot 2H_2O$ --------------	Rare
Calcite . . .	$CaCO_3$	

Bastin 66/ mentions secondary argentite (Ag_2S) and proustite ($3Ag_2S.As_2S_3$) as being very minor constituents of some ores, and Schrader 72/ states that horn silver (cerargyrite, AgCl) was an important mineral in the oxide zone of many veins.

GENERAL FEATURES OF OXIDATION

Oxidation effects have been of considerable economic importance. Rich deposits of native and horn silver were formed in the oxide zones of many of the veins, and it was the discovery and exploitation of these near-surface deposits that was responsible for the early prosperity and growth of the region. Most of these deposits were exhausted prior to 1900, but oxide deposits of marginal grade received attention in the years immediately preceding World War II.

As might be expected in an arid climate, where relatively high temperatures prevail, and where the irregular surface flooding is widely spaced in time, oxidation has been thorough in the upper portions of the veins. The effects extend as deep as 350 feet in veins on the higher slopes, where the water table is consistently low. However, the general limit of strong oxidation is about 100 feet, and in most veins the depth is between 50 and 80 feet. The transition from oxides to sulfides commonly takes place within a distance of 10 to 15 feet.

The products of oxidation, being derived from an aggregate of sulfide minerals, are numerous. Furthermore, differences from place to place in occurrence and quantity of the sulfide and gangue minerals add to the complication of the end products. However, diagnostic oxide minerals, textures, and structures occur in many veins. These aid in the reconstruction of processes of solution and deposition within the superficial zone and can be of value in the search for new ore bodies.

Role of gangue -- Locke has classified gangues as inert, and slowly, moderately, or rapidly reacting 73/. The predominance of quartz as a primary gangue mineral in these deposits might be expected to give an inert environment for oxidation processes. In some places in the veins this seems to have been true. In other places, where calcite was abundant, rapid neutralization occurred. As a general rule, though, the feldspathic nature of the wall rocks and the abundance of altered country rock and clay gouge within the veins has provided what Boswell and Blanchard term an environment of moderately slow neutralizer 74/.

Limonite -- In the following discussion of the products derived from the various primary minerals, the term "limonite" will be used broadly. In all specimens that were examined microscopically, the bulk of the iron oxides is microcrystalline, isotropic, and indeterminable as other than "limonite". Of widespread occurrence, however, are small amounts of goethite and jarosite. In some specimens hematite and plumbojarosite were observed, the latter in association with other lead minerals. The probable presence of some or all these minerals will be implied where limonite is mentioned.

Pyrite -- Pyrite is present in all the veins. This mineral, through reaction with oxygenated water, produces the powerful solvents ferric sulfate and sulfuric acid, which are effective agents in the oxidation of sulfide minerals 75/. Pyrite has been the chief source of the ubiquitous limonite, both from the direct production of ferric hydroxide after pyrite and from reactions of ferric sulfate with the other sulfide minerals.

Arsenopyrite -- The typical oxidized derivative of arsenopyrite is a granular intergrowth of scorodite and limonitic particles, built in a distinctive arborescent structure 76/. If the arsenopyrite was part of a complex sulfide mixture, the granular intergrowth is modified by the presence of a cellular boxwork structure, a granular fretwork in the matrix, and the presence of intergrown extraneous minerals, notably mimetite. In oxide specimens collected from the vein deposits of the Cerbat range, pale green to olive-drab granular and arborescent encrustations of scorodite coat the walls of oxidation voids. Limonite accompanies the scorodite but is not abundant. Cellular boxworks and granular fretworks do not seem to occur, but this may be an accident of collection. The association of extraneous minerals is well shown in a specimen from the Mollie Gibson mine, where numerous colorless to white tiny prismatic crystals of mimetite are intergrown with the scorodite.

Further evidence of the possible former presence of arsenopyrite is the occurrence in oxide specimens of apple-green stains. These are associated with the derivatives of sphalerite and galena, and are presumably ferrous arsenate 77/.

Sphalerite -- Zinc sulfide reacts readily with oxidizing solutions to produce zinc sulfate. The latter has a relatively high solubility and tends to be carried away by downward percolating waters. In the completely oxidized ores this process has been very effective, for no traces of zinc minerals remain. In partly oxidized ores, secondary products after sphalerite are present in small amounts. Small cracks in some sphalerite will effervesce with hydrochloric acid, indicating the possible presence of films of smithsonite, and sphalerite that has come in contact with cupric sulfate solutions has developed irregular veinlets and borders of covellite.

Though zinc has been lost, its former presence can be demonstrated. The ore deposits are characterized by an environment of moderately slow neutralizer, and under such a condition sphalerite tends to change into distinctive residual structures of limonite and limonitic jasper.

Examples of coarse cellular boxworks, fine cellular boxworks, and cellular sponges correspond with the three types described by Boswell and Blanchard 78/. The agreement is not surprising in view of the fact that these authors used two specimens from the Golconda mine of the Cerbat district in figures illustrating the typical development of coarse cellular boxwork.

Galena -- In contrast to the loss of zinc, lead is well preserved in the oxide zone. This is to be expected, as lead sulfide, reacting with oxidizing solutions, forms the highly insoluble mineral anglesite. Coatings of anglesite are common on partly oxidized galena, and kernels of such protected galena can be seen even at the surface of veins. Most of the anglesite has reacted with water containing carbon dioxide, and the anglesite has a coating of cerussite. In some specimens the reaction has been complete, and cerussite is the only lead mineral present. Cerussite is also relatively insoluble and is abundant in the oxide zone. Like sphalerite, some galena has reacted with cupric sulfate solutions, forming veinlets and rims of covellite.

Though the former presence of galena is readily detected from the occurrence of the insoluble sulfate and carbonate, it is also indicated by the development of residual structures of limonite and silica. Boswell and Blanchard describe cleavage boxworks, partially sintered crusts, ragged cellular structure, and an ochreous orange limonite color as diagnostic derivatives 79/. Cleavage boxworks are well developed, and their fine, closely-spaced, parallel cell walls are easily identified. The other features may be present but are difficult to distinguish with any degree of assurance.

Chalcopyrite -- Chalcopyrite is present only in minor amounts in the sulfide ores and therefore has not contributed significant quantities of material to the oxide zone. But where formed, the oxide products are of considerable variety. In the presence of acid solutions chalcopyrite is easily converted to copper sulfate. Hydrated forms of this, as chalcanthite and iron-copper chalcanthite, can be observed along the walls of drifts in many of the mines. The basic carbonates of copper, malachite and azurite, are abundant in the Clyde vein, and malachite occurs in small amounts in a few other veins. These minerals probably formed through reaction of copper sulfate with carbonate gangue material. Secondary chalcocite also occurs in the oxide zone of the Clyde mine, where the necessary neutral conditions for its formation seem to be due to the presence of carbonate gangue. In places oxidation of the chalcocite has produced cuprite. Continued action, possibly from the effect of ferrous sulfate, has resulted in the reduction of the cuprite to native copper. Cuprite and native copper were observed only in the Clyde mine, which has an unusual amount of chalcopyrite in the primary ore, and their development represents a special and not a general condition.

Covellite has developed through the action of cupric sulfate on sphalerite and galena. Minor amounts of covellite have formed, in similar fashion, from blebs and small veinlets of chalcopyrite that exist in partly oxidized specimens.

Due to the fine grain size and small quantity of chalcopyrite in the primary ores, characteristic limonite structures would not be expected and have not been observed in the oxide specimens.

Silver minerals -- The complex silver minerals were present in quantity in the upper portions of some of the veins. These would react easily with oxidizing solutions to form silver sulfate. Bastin determined a chlorine content of 80 parts per million in a water sample from

Tennessee Wash 80/. With such surface waters the silver sulfate should react to form cerargyrite. Some argentite would be expected where the reactions were not complete. Part of the silver sulfate in the middle and lower portions of the oxide zone should suffer reduction, resulting in the production of native silver. This order is borne out in the history of the mines, for horn silver was the chief near-surface ore mineral, and plates and wires of native silver were encountered at greater depth.

Gold -- Small quantities of gold have heightened the value of many oxide ores, through concentration resulting from the leaching away of sulfide minerals. In addition, some enrichment may have occurred through weathering and the mechanical downward shift of gold particles. Chemical enrichment is thought to have been negligible.

Other minerals in the oxide zone -- Small seams of selenite were observed along the footwall of the Silver Hill vein. These seams probably formed by the reaction of gangue calcite with sulfate solutions. Small white stalactites of calcite are currently forming on the back of the main adit in the Mint mine. The calcite has a rough, mammillary outer surface and a finely crystalline interior. Black coatings, which appear to be manganese oxide, are common on surface specimens of vein material.

INTERPRETATION OF GOSSANS

Some veins have no surface expression. Most have iron-stained gossans, and many project as strong ridges of quartz. Various features of oxidation could be used to advantage in detailed examination and prospecting of the veins. Stoped sections of veins often extend to the present surface, and some of these must have followed economic ore bodies. A few are reported to have lain beneath depressions along the strike of the veins. Prospecting for depressions which have resulted from the oxidation shrinkage of sulfide ore bodies might prove worthwhile. The method is complicated, however, by the fact that many veins contain large quantities of soft gouge, which can erode easily and produce similar effects.

Lead minerals are persistent in the oxide zone, and in places kernels of galena occur at the surface. These obvious indications of ore should be sought. That they may have been overlooked, despite the long history of prospecting and mining in the region, is exphasized by the fact that indications of this type led to the discovery of a small but relatively high grade deposit in the Mineral Park district in the summer of 1947.

Less obvious, but perhaps of equal value, are the diagnostic boxworks and limonite residues left in the gossans by sphalerite and galena. Systematic and detailed search for these derivatives could be of considerable value in guiding exploration, for they are frequently well preserved. It should be pointed out, though, that their absence in an outcrop might not mean a lack of sulfides at depth, for they may be mutually interfering to a certain extent or may be masked by derivatives of pyrite. If the pyrite content is greater than one-quarter the total volume of the mixed sulfides, the diagnostic derivatives will fail to develop 81/. This ratio undoubtedly is exceeded in places in these ores.

SECONDARY ENRICHMENT

Secondary enrichment has been of no consequence in the vein deposits. Zinc was removed from the oxide zone but was not precipitated at depth. Lead was oxidized, but the products migrated little, if at all, from the site of the original sulfides. The same seems to have been true of the silver minerals, inasmuch as high-grade silver ore came from the oxide zone. Furthermore, the silver sulfarsenides and sulfantimonides are believed to be primary. Thus, there has been no appreciable impoverishment above the water table, and no enrichment below.

Cupric sulfate solutions, however, derived in small quantity from chalcopyrite, in places have penetrated the primary mineral zone. The result has been the rare development of insignificant quantities of chalcocite after pyrite, and covellite and chalcocite after chalcopyrite. More common has been the formation of films of covellite on sphalerite and galena. Technically this amounts to copper enrichment, but it has not added to the value of the ore.

WALL ROCK ALTERATION

Effects of wall rock alteration that are visible in the field ordinarily extend only a few feet from the veins. The most obvious alteration occurs in the numerous mafic dikes that occupy one or both walls of many veins. However, deuteric alteration is a common feature of such dikes, especially lamprophyres, and hydrothermal action cannot be assumed to be the sole agent. Furthermore, the available portions of many of the veins are solely within the oxide zone, and there alteration effects have been further modified by supergene processes.

Comprehensive investigation of the alteration has not been attempted, but a series of samples collected underground in the Tennessee-Schuylkill mine has given an indication of the type and degree of change imposed on granite gneiss, the prevailing rock type of the mineralized area. Samples were taken along the cross-cut at the 1,000 foot level from the shaft to the vein. The vein is approximately five feet wide where intercepted by the cross-cut. The back is timbered, but on the west wall, where sampling was started, 12 inches of white quartz containing narrow seams of sulfide minerals is visible.

The last sample taken was 150 feet west of the Tennessee vein. However, a parallel veinlet occurs 50 feet west of the vein, and the effective distance for solutions to travel to this specimen is only 100 feet. The rock is a fine-grained injection gneiss composed of quartz, feldspar, pyroxene, and biotite. Selective alteration has affected about 25 percent of the minerals, whereas the rest are clear and fresh. Part of the alteration may be deuteric, but the presence of abundant pyrite, which is not a normal component of the gneiss, indicates that mineralizing solutions have penetrated the rock. Secondary products are biotite, formed along the course of a veinlet of pyrite and chlorite; chlorite, muscovite, and biotite, after diopside; chlorite, epidote, and magnetite after primary biotite; and sericite, chlorite, epidote, zoisite, and clay mineral in microcrystalline aggregates after feldspar. A well formed vermicular crystal, 0.13 by 0.06 millimeter in size, suggests that the clay mineral is kaolinite.

With the exception of the occurrence of calcite, formed in some specimens after biotite and feldspar, this suite of secondary minerals characterizes the country rock to within a short distance of the vein. Alteration does not seem to have affected more than 25 percent of the minerals, and in some specimens not more than 10 percent. The first change in the alteration suite noted in a specimen taken 30 feet west of the vein. The occurrence of a parallel veinlet 20 feet west of the vein means a distance of 10 feet from a mineralizing channel. This specimen is a fine-grained garnetiferous granite gneiss about one-quarter selectively altered to chlorite, calcite, epidote, pyrite, sericite, clay mineral, and possibly biotite. It is similar to specimens farther out, except that secondary sphene occurs as replacement lenses in biotite.

A specimen taken 10 feet from the main vein is completely altered and comparable in every respect to rock immediately adjacent to the vein. The alteration is anomalous, though, and must have been caused by a solution channel not apparent on the wall of the cross-cut. The probable presence of such a channel is supported by the occurrence of veinlets of clay mineral in the specimen.

A specimen of garnetiferous granite gneiss, taken five feet from the vein, is only 10 to 15 percent altered. The secondary minerals are chlorite, epidote, pyrite, biotite, sericite, and clay mineral. Sphene is present but does not seem to be secondary, though it was expected on the basis of its occurrence in the specimen 30 feet from the vein.

The rock adjoining the vein, and in a zone not over two feet wide, is thoroughly altered. A fine-grained gneissic texture is visible, but, unless some primary quartz is present, no original minerals have survived. Bleaching is prominent, and the rock is light gray to white. Irregular, interlocking grains of quartz make up 35 to 40 percent of a specimen that was cut next to the vein. Apparently contemporaneous with the quartz is approximately 3 percent white mica, scattered through the section as tiny plates. Random, subhedral crystals of pyrite are earlier than the quartz and white mica, or contemporaneous, for the pyrite is corroded by the latest minerals. The latest minerals are sphene, sericite, and clay mineral. The sphene makes up approximately 5 percent and the sericite and clay 55 percent of the rock. Most of the sphene occurs as long stringers and lenses replacing the plates of white mica. It follows the foliate structure of the mica with exceptional regularity in most places. The balance of the sphene occurs as irregular grains and tiny crystals associated with the sericite and clay mineral. In the specimen 10 feet from the main vein, sphene is intergrown with sericite in a comb crust that lines the walls of a microscopic clay veinlet. The sericite and clay in this thoroughly altered rock are about equal in amount and are present in microscopic intergrowths. Each was observed to cut the other in microscopic veinlets, and the assumption is that they are essentially contemporaneous in age. They both corrode and replace the quartz and white mica.

On the basis of the foregoingobservations, the alteration processes can be divided into three stageds.

(1) First is the widespread but weak development of chlorite, pyrite, epidote, sericite, clay, and minor amounts of biotite and calcite. This aptly can be termed propylitization, for it is similar to the stage of propylitic alteration that characterizes many mining districts 82/.

(2) Second, and restricted to a narrow zone adjoining the vein, is a stage of silicification, with the development of flakes of white mica. Pyrite may or may not be contemporaneous with this stage. A transitional zone with the preceding propylitic minerals probably exists, but in the specimens examined the earlier alteration products, possibly excepting pyrite, have been destroyed.

(3) The last and presumably most intense stage is distinguished by the formation of sericite, clay mineral, and a small quantity of sphene. These minerals replace the quartz and white mica and in extreme alteration should be the only minerals present.

That the ultimate stage is represented principally by sericite and clay mineral is shown by totally altered specimens of diabase, granite porphyry, and hornblende schist that were taken from the walls of three different veins. Aside from a few residual quartz grains in the granite porphyry, relict textures are the only remains of the original rocks. The specimens are yellowish gray, consist of about equal amounts of sericite and clay, and are stained to varying degrees by limonite. The specimens came from the oxide zone, and pyrite or sphene, if originally present, could easily have been removed. Furthermore, some of the clay could be of supergene origin. The bulk of the clay, however, is believed to be hypogene, on the basis of the clay observed in the wall rocks 1,000 feet below the surface of the Tennessee vein. The formation of the same final alteration products, regardless of the initial type of wall rock, shows a strong dependence on the composition of the solutions and not on the composition of the wall rock. As discussed by Butler 83/, this is an expected feature of hydrothermal alteration.

A particularly interesting occurrence of clay mineral was noted in the roof of the south stope at the 1,000 foot level of the Tennessee-Schuylkill mine, in June 1948. A white substance was seen approximately in the center of the ore-shoot, within an area of sulfide minerals. It was thought to be perhaps late silica or a sulfate mineral. Detailed examination showed it to be associated with late quartz and crustified calcite veinlets that cut earlier quartz and sulfides. The white substance itself is an open space filling, and in one specimen it is situated between veinlets of quartz and calcite. It contains tiny pyrite crystals and irregular grains of sphalerite, as does the calcite. In hand specimen it has a distinct pearly luster. Under the microscope it resolves into a microcrystalline aggregate of grains that have an average diameter of 0.02 millimeter and extremely low birefringence. Immersion oil determinations gave a refractive index of 1.562, with another index that seemed to be about 1.558. On the basis of the refractive indices, the pearly luster, and the nature of occurrence, the mineral is tentatively identified as nacrite. The limited data correspond well with the descriptions given by Ross and Kerr 84/ for this mineral. Precise determinations are planned, and it is hoped that further study of the occurrence can be carried out in the future. Though its source is unknown, its hydrothermal nature seems indisputable.

Successive stages and zones of wall rock alteration have been recognized in many mining districts. Features similar to those that have been described above occur at Cerro de Pasco. In that locality Graton and Bowditch 85/ recognize a feeble phase, characterized by chlorite, calcite, and epidote; a moderate phase, marked by sericite, pyrite, and quartz; and an intense phase, in which the rock is converted to quartz, pyrite, kaolin (dickite), and alunite. Residual sericite is common in this last phase. The mineralogy is similar to that in the altered wall rock of the Tennessee vein, and the high-temperature dickite is noteworthy. With alunite, dickite is supposed to represent a late acid condition in the mineralizing solutions. Sales and Meyer 86/ also mention dickite as occurring near the hot center of the Butte, Montana camp and in association with sericite. This seems analogous to the sericite and nacrite (?) associated with the Tennessee vein.

The introduction of sphene in the last and most intense stage of alteration is unusual. Sphene is not uncommon, however, as a deuteric alteration product in igneous rocks and is present in many contact metamorphic rocks. Gillson discussed such occurrences in his paper on the Pend Oreille district 87/. The pneumatolytic or hydrothermal origin of sphene in igneous and metamorphic rocks indicates that its association with hydrothermal vein formation is not illogical. Recent analyses by Sahama 88/ show that the sphene latticé, of the specimens examined, contains fluorine in remarkable amounts. Jaffe 89/ has also demonstrated the presence of fluorine in a number of specimens of sphene. This is perhaps significant as to the mode of origin of sphene. It would be interesting to know if any correlation exists between the amount of contained fluorine and a deuteric or hydrothermal source.

VEIN STRUCTURE AND EXPRESSION

With few exceptions, the veins are well-defined tabular bodies. Gouge and breccia line most of the walls, and the walls break freely from the country rock. Frozen walls, cemented by primary quartz deposition, are less frequent but not rare. The fractures occupied by the veins are regular and in large scale are straight or broadly curving. In detail, changes in strike and dip are numerous but are not pronounced. Splits and "horsetails" occur in places in conjunction with small changes in vein orientation. As shown in Plate 4, linkage of veins along the strike is common. In the eastern part of the Chloride district, where most of the veins have a northwest strike, dips in the upper portions of some veins are opposed to those in other veins. The dips are steep, and exploration has not gone deep enough to disclose possible intersections.

A common feature in the veins is a laminated structure formed by alternating layers of yellowish gray gouge and quartz. The quartz is typically vuggy and may or may not contain sulfides. As an example, a vein may have four or five layers of quartz that are 1 to 6 inches across, separated by layers of gouge of similar thickness. Variations occur, but the seams of quartz rarely exceed two feet in width. The structure is illustrated in the sketch of Figure 30. Much of the gouge contains crushed and rolled fragments of country rock and quartz.

Most of the veins are only a few feet wide. Widths up to 80 feet occur, but wide veins more accurately can be called mineralized zones,

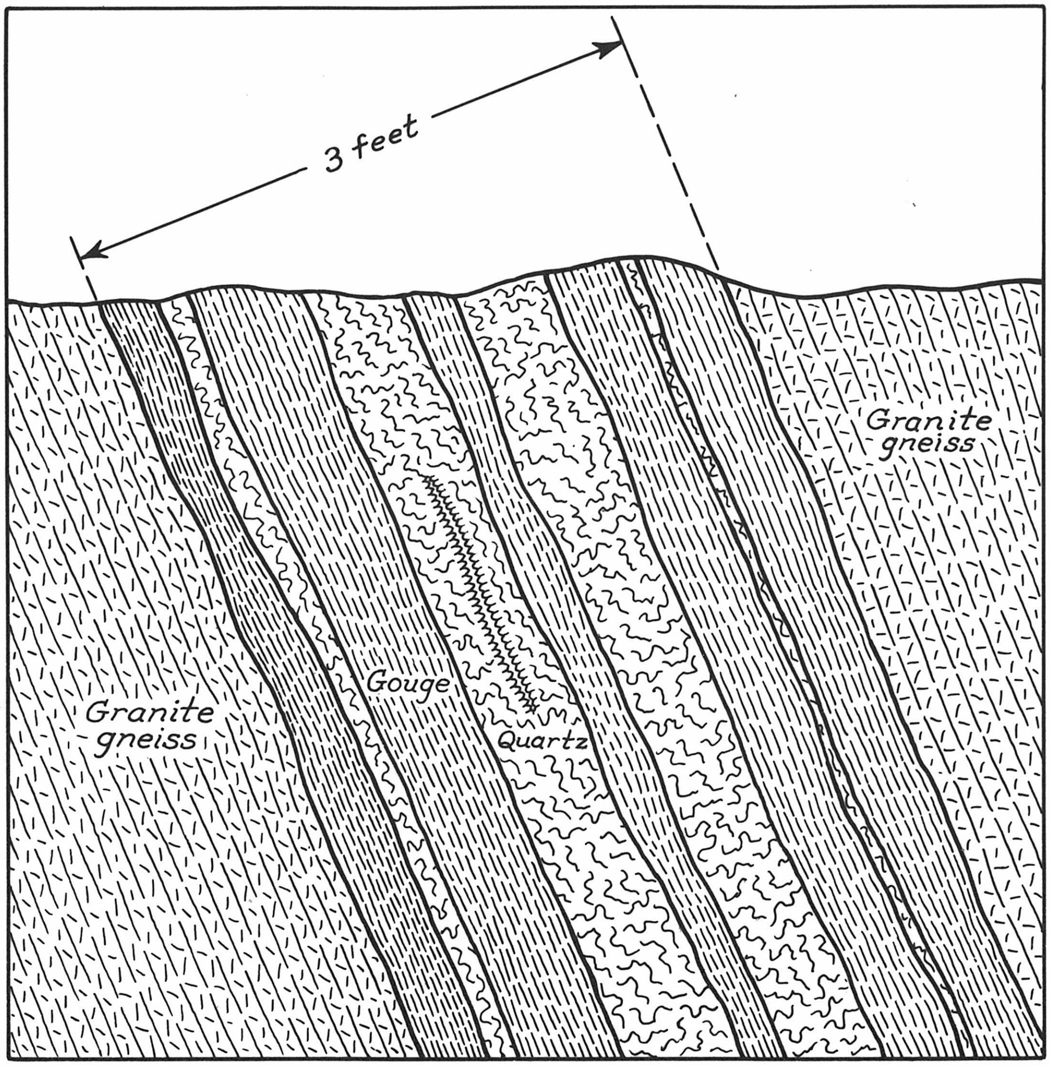


Figure 30 -- Transverse section of Alice vein showing laminated structure formed by alternating layers of quartz and gouge.

for they have a composite structure in which a number of closely-spaced narrow veins are separated by gouge and country rock which has been altered, sheared, crushed, and in places silicified. Considerable variations in thickness occur, and portions of some veins have no surface trace. In such places indications of mineralization, in the form of small quartz stringers or altered country rock, are usually present in prospect holes along the line of strike. Most of the veins are continuous and distinct at the surface. Many extend for over a mile, and the Tennessee vein can be traced two and one-half miles.

The surface expression of the veins is diverse. Where a wide composite vein zone occurs, the combination of iron-stained quartz and altered schist and gneiss gives a reddish brown to purplish brown outcrop, flush with the adjacent surface in most places. In some narrow veins strong quartz ledges protrude several feet above the general surface. The quartz in these ledges is stained yellowish to reddish brown and black, and some is honey-combed from the removal of primary sulfides. Ledges of this type occur along the Mary Bell and North Georgia veins, and outcrops of fairly solid quartz stand as much as 12 feet wide and 10 feet high. An outcrop of the Mary Bell vein is shown in Figure 31. A composite type vein with a less prominent outcrop, the New Tennessee, is shown in Figure 32.

GENERAL FEATURES OF PRIMARY DEPOSITION

Certain aspects of deposition are common to all the veins. One of the most obvious features is an abundance of comb and rosette quartz with associated open vugs and druses. Euhedral crystals of quartz one-half to three-quarters of an inch in diameter are not unusual. Sulfide minerals older, younger, or the same age as the quartz, are associated

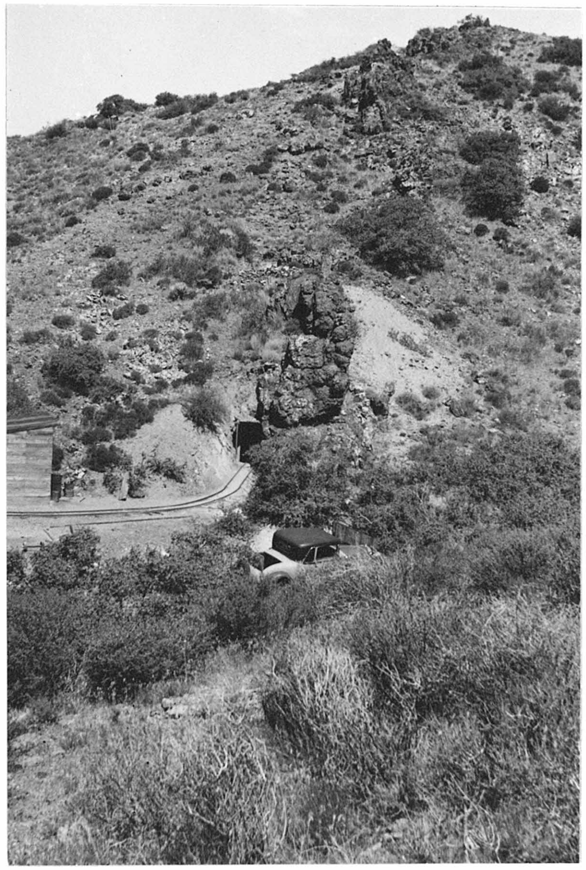


Figure 31 -- Outcrop of Mary Bell vein. Prominent quartz ledge stands as much as 10 feet above surrounding country. View looking north.

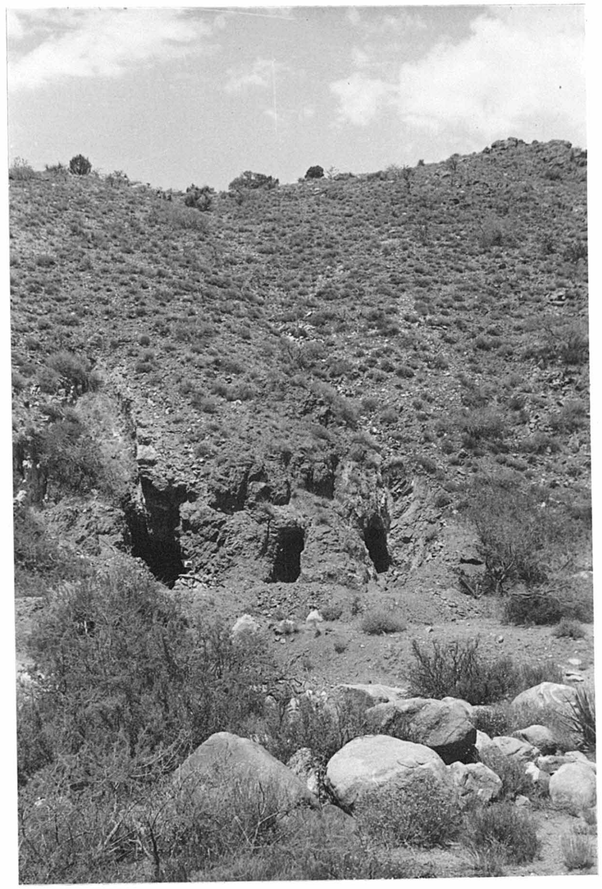


Figure 32 -- Outcrop of New Tennessee vein. Essentially a sharp zone of sheared, brecciated, altered, and silicified amphibole schist. Note topographic depressions formed along gouge selvages on either wall. Vein is 30 feet wide. View looking north.

with many of the combs. In addition to open combs, crustification structures, formed by successive layers of minerals, are also abundant. Many of the quartz seams that are part of the laminated structures in the veins are formed of these crustified fillings. A line of small vugs characteristically marks the center-line of a filling. An example of symmetrical filling of a small fissure within a vein is shown in Figure 33. These features imply that open space filling was an important factor in the formation of the veins. Replacement of hypogene minerals by one another operated to a large extent, and replacement of the wall rocks was widespread but chiefly by quartz, pyrite, sericite, and kaolin. The vein boundaries are sharp, and the ore minerals seem to have been deposited entirely within the fissures.

Variable crystallinity is another characteristic feature, especially in the quartz. In some places the sulfide minerals range from microscopic grains to crystals more than 3 centimeters in size, but in most specimens the range is from a few millimeters to 1 or 2 centimeters. In quartz, however, it is not uncommon to find a chalcedonic variety immediately adjacent to euhedral crystals. Layers of cryptocrystalline quartz occur in crustified bands and usually have a delicate scalloped banding that is suggestive of rapid deposition 90/. A few specimens were observed in which fragments of early quartz and country rock have been surrounded by successive delicate layers of cryptocrystalline and finely crystalline quartz, producing a cockade structure 91/. (See Figure 34).

CLASSIFICATION OF DEPOSITS

Lindgren classed these deposits as "pyritic galena-quartz veins", comparable to those at Freiberg, and placed them in his mesothermal

<u>Figure 33</u> -- Small fissure filling. New Moon mine, south face of drift, 150 foot level, summer, 1948. Note symmetrical deposition of quartz and sulfides in early crusts along both walls, followed by central filling of quartz. Line of tiny vugs has been left in center of this late quartz band.

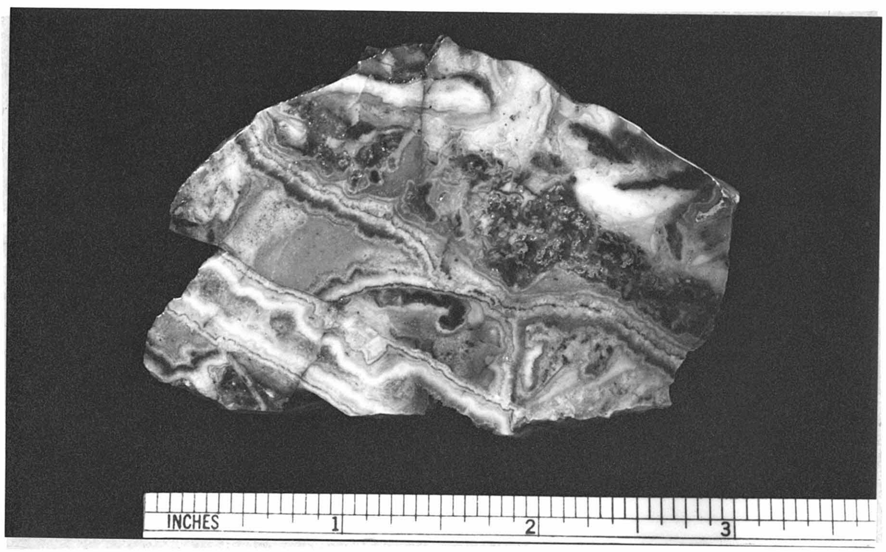


Figure 34 -- Delicately banded, chalcedonic and fine-grained quartz from Aurora vein. Note that early brecciation, with subsequent cockade-type deposition, has been followed by later fracturing, with formation of finely banded veinlet in lower left part of specimen.

division 92/. Diagnostic features include the predominance of the base metals, the regularity of the veins, and the well-defined, mostly free walls. Yet, if Lindgren's system is to be followed closely, the veins fit his epithermal classification even better. The crustified fillings, comb-structures, drusy cavities, and vugs are indicative of deposition under conditions of relatively low pressure, where openings can be self-sustaining. The declicate banding and the occurrence of cryptocrystalline quartz suggest pressure and temperature conditions that could be maintained only at comparatively shallow depths. Furthermore, the presence of complex sulfo-salts of silver is usually assumed to be indicative of low-intensity or shallow conditions.

The compromise which is obviously needed, if the deposits are to be fitted into a hydrothermal depth-zone, is provided by Graton's leptothermal zone 93/. The general description of this category fits these veins nicely and aligns them with base-metal deposits of the type found in the San Juan mountains of southwestern Colorado, and with the veins of Casapalca, Peru 94/.

MINERAL ZONING

No evidence was found of distinct zoning, either vertical or horizontal within the veins. On the contrary, changes in texture or structure follow no consistent pattern, and all the data that were collected on the mineralogy, and the percentages of various metals, show a uniform mineral distribution. Veins on the edges of the mineralized belt contain the same minerals, in the same average proportions, as those in the center. The ore in the bottom of the Tennessee-Schuylkill mine is essentially the same as that found in veins near the crest of the range, though in places this means a vertical difference of over 3,000 feet. That vertical zoning of the precious metals must have obtained is suggested by the reportedly rich values mined from the oxide zone, for present ores do not seem capable of providing extreme values, even through complete leaching and alteration of the sulfides. If this were true, however, the veins at high elevations should still contain better values than those at low elevations, and such is not the case. Rather, two veins that have produced ruby silver in quantity in the last 20 years, the Diana (Arizona Magma), of the Chloride district, and the Keystone, of the Mineral Park district, are both at low elevations. The distribution of rich silver sulfides appears erratic and was probably controlled by the localized coincidence of permeable opeinings with a period of high silver concentration in the mineralizing solutions.

According to Garrett 95/, local horizontal zoning occurred in some of the ore shoots in the Tennessee-Schuylkill mine. Variations in other veins also have been reported, and portions or all of some ore shoots are said to have been characterized by high gold, or lead, or zinc. Again, these variations may have been dependent on the openings that were available at any one time to changing mineral solutions.

A zonal arrangement is present in the distribution of the vein fissures, for they occur in a long belt, at the center of which is the disseminated copper mineralization of the Mineral Park district. (See Figure 27). A case might be made for metal zoning on the basis of the cupriferous area surrounded by lead-zinc deposits. But, the latter also occur within the "copper zone" and are separated by a break in time of mineralization. The factors of time and structure have been paramount in determining the zonal relations of these two periods of mineralization.

ORE SHOOTS

Despite the abundance of veins, comparatively large quantities of ore have been found only in the Tennessee-Schuylkill and Golconda mines. In the Tennessee-Schuylkill the ore shoots range from 1 to 15 feet in width, but the usual width is about 5 feet 96/. The width of ore in most veins is from 1 to 5 feet.

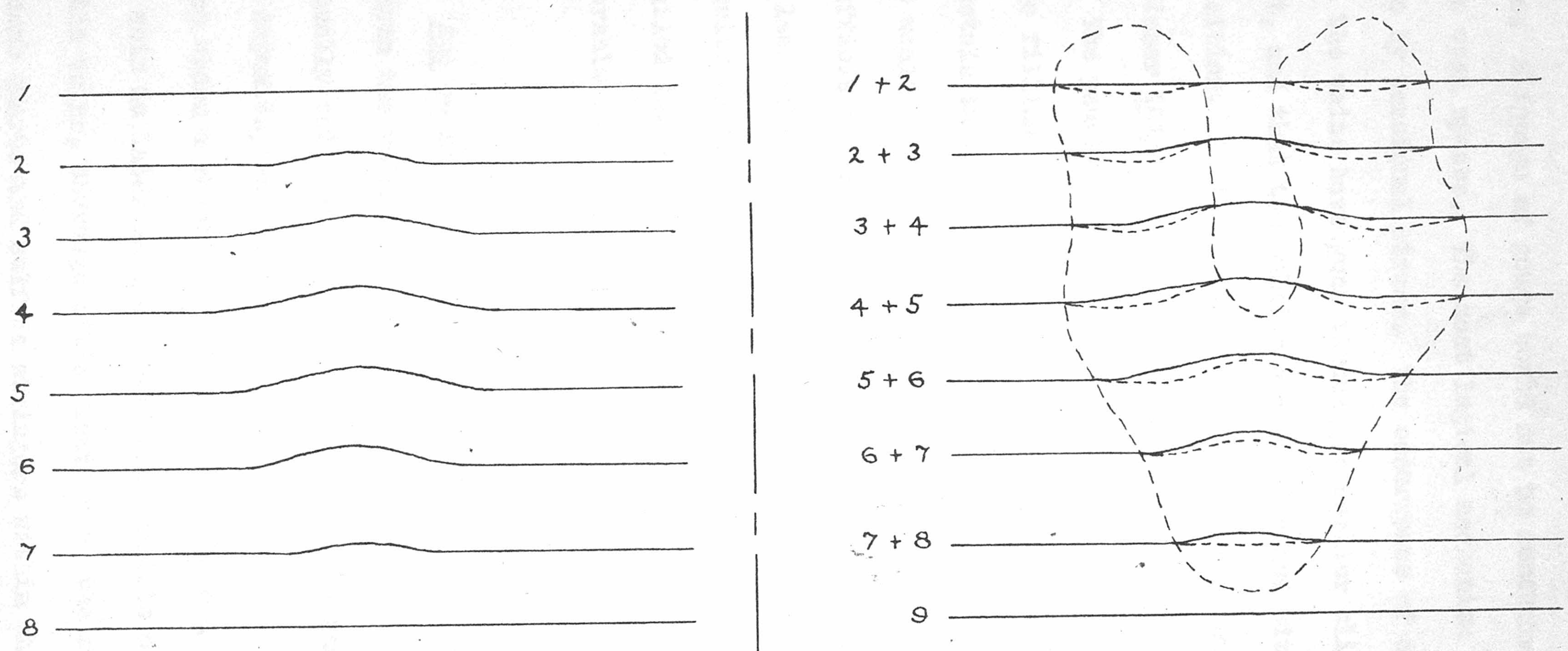
The lack of ore shoots of appreciable size may be due in many places to the quantity of gouge filling in the veins. Sales 97/ has stated, "A gouge filled fissure appears to be distinctly unfavorable to ore deposition, probably in part because the gouge chokes the fissure and prevents the access of mineral bearing solutions, and in part because the movement along such a fissure is so nearly continuous as to give no chance for the deliberate and undisturbed chemical action which seems requisite for the formation of large, clean bodies of ore."

Large, clean bodies of ore certainly have not been encountered in the exploration of most of these veins. Rather, the typical occurrence of ore is in discontinuous layers and lenses, which are situated on the hanging wall, foot wall, or within the central portion of a vein. The ore in many veins is surrounded by gouge, which needs support during mining to prevent dilution of the ore. Much of this gouge, which has resulted from attrition by fault movement and hydrothermal kaolinization and sericitization of the country rock, formed prior to the deposition of the sulfide minerals. This early presence of impermeable material, at least locally choking the fissures, has apparently prevented the deposition of any large amounts of ore in many of the veins. The dominance of gouge, however, is not universal. Some veins are predominantly quartzose and have tightly frozen walls.

Segregations of ore seem to have formed where open spaces were available for direct deposition of the valuable minerals. Even in heavy gouge, bands and lenses of primary minerals display comb structures, vugs, and crustification that could only form in cavities. There is no obvious wall rock control in the location of ore, and fillings are as wide in one rock as another. The veins may pinch and swell, but there is no distinct correlation with any rock type. If the fissures passed into volcanics or sediments radical changes might be expected 98/. As it is, the high-grade metamorphic and intrusive igneous terrane, despite its petrologic variety, has acted as a uniform host for fracturing.

In view of the displacements indicated by the striations and slickensides in the veins open spaces favorable for ore shoots could be a function of changes in the configuration of the fissures. Garrett 99/ states "that ore shoots in the Tennessee-Schuylkill mine occur where the vein has changed to a more than average northwesterly strike." The distribution of stopes (See Plate 9) suggests that the presence of troughs and ridges in the vein configuration also may have been of importance. Oblique-slip movement seems to have characterized most of the veins in the region including the Tennessee. The stoped area just south of the Schuylkill shaft is roughly "V" shaped and has a northward rake. Such an opening could be produced by oblique-slip movement parallel to a northward-raking elongate dome in the fissure walls. The shape of such a dome would not remain absolutely the same along its length. Any longitudinal displacement would produce openings where a certain radius of curvature in one wall was brought opposite a different radius of curvature in the other wall. The resulting opening would be "V" shaped. The sketch of Figure 35 illustrates the mechanism that might have operated. This suggestion is plausible but over-simplified. Verification of this type of control could be gained through the use of a three-dimensional analysis such as that suggested by Newhouse 100/.

Where gouge forms a large part of a vein-filling and is accompanied



Elongate dome in vein surface shown by structural contours.

Shape of opening produced by dislocation parallel to longitudinal axis of dome, resulting in superposition of structural contours as shown.

Figure 35 -- Sketch illustrating possible mechanism for evolution of V-shaped ore shoot in Tennessee-Schuylkill mine.

by striations and slickensides shear or slippage of the walls is indicated. However, layers and lenses of gangue and sulfide minerals commonly occur as open-space fillings within thick envelopes of this gouge. Slippage of gouge would not be conducive to the production of these open spaces. The most logical mechanism is pulling apart of the gouge by tensional stress. The occurrence of such fillings suggests that the veins have gone through an earlier slipping and a later pulling apart, and that the pulling apart coincided with a phase of sulfide deposition. A similar sequence at Pachuca, Mexico has been discussed by Wisser 101/.

The paucity of sizable ore bodies might be due in part to the strong gouge filling of many veins. Further explanation might lie in a scarcity of metals in the hydrothermal solutions, in a lack of fissure structure that would produce openings during dislocation of the walls, or in insufficient pulling aprat of the walls where that mechanism operated. The lack of suitable structure is open to question, however, as the majority of the veins have undergone only very shallow exploration. Detailed investigation of any single vein might reveal indications of favorable structures at depth.

AGE AND GENESIS OF DEPOSITS

Age -- The age of the mineralization is defined by the relations between the veins and the rhyolite and andesite dikes. It has been generally believed 102/ that the rhyolite dikes are younger than the ore deposits, but detailed mapping has failed to confirm this. In every place where a rhyolite dike and a vein have a clearly exposed contact the vein is later in age. Evidence consists of offsets of the dikes by the veins, thorough silicification of the rhyolite, and the presence of comb quartz and sulfide stringers within the dikes. No offset or truncation of a vein by a rhyolite dike was observed. The few small andesite dikes that were seen in association with the veins are hydrothermally altered and presumably are also pre-mineral in age, though such occurrences could be intra-mineral. If the assumption of a Tertiary age for the rhyolite and andesite dikes is valid the mineralization is of course Tertiary in age. The veins transect the disseminated copper mineralization of Mineral Park, which is also younger than the volcanic dikes.

Genesis -- If possible, generalizations regarding the origin of an ore deposit should be made 103/. Such generalizations must necessarily be based upon the observable relationships that exist between the geology and the mineralization of an area. In the Wallapai district certain features are significant, and they are listed as the framework for interpretation.

1) Most obvious is the spatial association of mineralization with the Ithaca Peak porphyry stock of the Mineral Park district (See Figure 28). Disseminated sulfide mineralization is localized within this stock and is at the geographical center of the belt of fissure vein deposits. It is noteworthy that this general pattern of "porphyry" intrusion, associated disseminated copper mineralization, and superimposed and surrounding lead-zinc fissure deposits is repeated in many districts 104/. Analogy is especially strong with the Bingham, Utah district where a center of mineralization has developed in one monzonite stock, whereas a nearby monzonite stock has no obvious relationship to the mineralization 105/.

2) Pre-intrusion structure was a factor in the emplacement of the Ithaca Peak porphyry. The Chloride district sill was injected into a steeply-pitching anticline, and folds guided at least part of the Mineral

Park stock. No lines of shear or faulting were recognized that might have helped localize the intrusion, but post-intrusion stress is indicated by secondary foliation in the granite porphyry.

3) The pattern of the veins was controlled by pre-vein structure. A strong northwest-trending joint system characterizes the region. Dikes both older and younger than the Ithaca Peak porphyry have followed these joints and show them to be features of long standing. Many of these joints became mineralized faults, and the majority of the veins follow this northwest trend. In the western part of the Chloride district the veins tended to form along fractures that are concordant with the anticlinal structure of that area, again a reflection of a pre-vein geologic feature.

4) A period of unknown but presumably long duration separates both the disseminated sulfides and the fissure vein deposits from the time of intrusion of the Ithaca Peak porphyry. This period is indicated by the injection of pegmatite and aplite, lamprophyres, and andesite and rhyolite dikes, all of which follow the Ithaca Peak porphyry and precede mineralization.

Interpretation of relations -- On the basis of the usual close areal relationship between ore deposits and intrusive igneous masses the inference is frequently made that the mineralizing solutions have been expelled directly from those masses 106/. A direct genetic connection between the Ithaca Peak porphyry and these ore deposits does not seem reasonable, however, owing to the time interval that elapsed between intrusion and mineralization, and because of the injection of a variety of dikes during that interval. The interposition of silicic and mafic satellitic dikes, as a common occurrence in mining districts, has been pointed out by Hulin 107/. He showed, through a statistical study, that the usual sequence is 1) major intrusion, 2) silicic satellitic intrusion, 3) mafic satellitic intrusions, and 4) mineralization. Inasmuch as the diaschistic dikes are explained as differentiated magma facies which have come from some depth beneath the exposed major intrusion, the mineralizing solutions are likewise attributed to a source at depth. This easily leads to the conclusion, drawn for example by Spurr 108/ and Loughlin 109/, that the satellitic dikes and the mineralizing solutions have a common source and are merely drawn off at different times.

Similar reasoning might be applied to these Cerbat range deposits were it not for the complicating appearance of andesite and rhyolite dikes, apparently later in age than the diaschistic dikes but still earlier than the mineralization. Accounting for them as further differentiation products of the body that yielded the lamprophyres is difficult. They more likely represent new magma, and they separate the mineralizing solutions from a possible Ithaca Peak porphyry source even more effectively than do the diaschistic dikes. The source of the solutions becomes completely speculative.

Structural control seems to be the best explanation for the close areal association of the ore deposits with the Ithaca Peak porphyry. In a paper that further emphasizes pre-mineral diaschistic dike injection Hulin 110/ stresses structural control as determining the association of intrusives and ore deposits. Disturbances during emplacement of an intrusion are held to prepare the ground prior to mineralization by weakening the invaded and overlying rocks and allowing relief of strain already present. Contraction due to solidification and cooling of the body is suggested as the cause of brecciation in porphyry copper deposits and of recurrent fault movement that maintains permeability of a district during mineralization.

On the basis of the evidence that the vein pattern has been controlled largely by pre-vein structure, Hulin's proposal that intrusion emplacement weakens the invaded and overlying rocks, allowing relief of strain already present, might be applicable. Such relief, along the set of northwest-trending strong joint planes and along the fractures controlled by the anticline in the Chloride district, may have served to block out the belt that was later mineralized. However, effects due to possible contraction are not so easily discovered. Only part of the Mineral Park stock and none of the Chloride district sill was brecciated. As pointed out by Pennebaker 111/ and Anderson 112/, local or special brecciation is not compatible with general shrinkage. Furthermore, large rhyolite dikes occur within the disseminated sulfide zone, and they are as thoroughly shattered as the surrounding granite porphyry. The intrusion was solidified prior to the intrusion of the dikes and was apparently cooled. Brecciation later in age than the rhyolite must be attributed to some cause other than shrinkage of the granite porphyry.

Recurrent faulting followed the emplacement of the Ithaca Peak porphyry and preceded mineralization, and intermittent movements occurred during the period of mineralization. It seems likely that the earlier faulting, especially that accompanying the injection of the lamprophyre dikes, could have resulted from intrusion shrinkage effects. The intramineral dislocations of the fissure vein deposits, however, following rhyolite dike injection and later in age than the disseminated sulfides, seem too remote in time to be a function of contraction of the Ithaca Park porphyry.

Conclusion -- The association of the ore deposits with the intrusive stock of the Mineral Park district is too close to be fortuitous. Yet, apparently the intrusion has provided neither the mineralizing solutions nor complete structural control. Where cause and effect cannot be demonstrated between two related features, the application of logic results in the treatment of both as effects of some other cause. Therefore, tectonic action is called upon, first to explain the localization of intrusion, and second to provide the locus of ore deposition. The presence of a major guiding channel for hydrothermal solutions is suggested by the symmetrical pattern of mineralization, which has a distinct mineralogical center of disseminated sulfides and a structural center of brecciation. Tectonic action around this center, preceding and accompanying mineralization, is indisputable. The postulation that such a channel formed at an early stage of tectonic activity, and thereby served to determine the general course of magmatic intrusion, is admittedly based on circumstantial evidence. The only obvious factors controlling intrusion are the folds in the invaded rocks. However, external stress was present after intrusion and may have preceded or accompanied it. The thesis of tectonic control for both intrusion and associated ore deposition is strengthened by the sequence of faulting, intrusion along "conduit faults", continued faulting, and mineralization that has been described for other districts. Examples are Ely, Nevada <u>113</u>/, Morenci, Arizona <u>114</u>/, and Magdalena, New Mexico <u>115</u>/.

DISSEMINATED SULFIDE DEPOSIT

An observer approaching from the west cannot fail to be impressed by the reddish colored cluster of peaks that mark the Mineral Park district. These peaks, set in a mountain range that is prevailingly gray, invite inspection. Such inspection shows that the color comes from an iron-stained capping, which lies over a thoroughly fractured and mineralized portion of Ithaca Peak granite porphyry. Closer inspection reveals that the mineralization is of the well-known disseminated or "porphyry copper" type.

Distribution of mineralization -- An area of more than four square miles, in the northeastern portion of the Ithaca Peak porphyry intrusive stock, has been outlined (See Figure 27) as containing the rocks that are most strongly shattered and mineralized. This is an arbitrary outline, for the degree of mineralization varies within the borders, and the outer limits are gradational rather than sharp. Also, strong mineralization may occur locally outside this main brecciated mass. An example is the thick tongue of porphyry that extends through Union Basin to the Golconda mine. This tongue is strongly fractured and has a reddish-brown capping. Though chiefly contained within the Ithaca Peak porphyry the mineralization is not restricted to it, for in places the mineralization passes across the intrusive contact into the pre-Cambrian Cerbat schist and gneiss. In the canyon cutting the north central part of S 13, T 23N, R 18W, signs of mineralization were traced outward 1,000 feet into granite gneiss. Large rhyolite dikes which traverse the Ithaca Peak porphyry are mineralized, as are septa and pendants of pre-Cambrian schist and gneiss.

Features of hypogene mineralization -- The primary minerals consist of abundant quartz and pyrite, and minor amounts of chalcopyrite and molybdenite. A few specks of bornite were observed in one specimen. As is typical in this type of deposit, these minerals occur both as fracture fillings and as specks and grains scattered through unfractured rock. Sphalerite and galena occasionally occur in small veinlets, which seem to be younger than the other veinlets. The sphalerite and galena are believed to be the same age as the large fissure-vein deposits of lead and zinc that cut across the disseminated sulfide deposits.

The strongly mineralized areas coincide with thoroughly shattered rock, where hydrothermal flooding and the formation of closely spaced veinlets has been possible. The veinlets in many of these areas are separated by only a fraction of an inch, and individual blocks of rock are rarely more than a few inches across. The fracture pattern is an intricate network, which rarely shows displacements at intersections. Observations made at widely separated places within the main mineralized zone suggest that the strongest veinlets favor strikes west-northwest and east-northeast. In detail, however, the veinlets seem to follow every conceivable strike and dip. Typical patterns are shown in Figures 36 and 37.

The veinlets commonly range from one-quarter inch in thickness down to mere seams. However, thicknesses of an inch or more are not rare. The larger veinlets typically contain vugs between crystals of quartz and pyrite.

Veinlets of quartz and pyrite that cut veinlets of quartz, pyrite, and molybdenite suggest that molybdenite was introduced in an early stage. Chalcopyrite and the few specks of bornite that were observed in polished section characteristically occur as blebs within pyrite and seem to be later in age. Some of the chalcopyrite, however, occurs as individual

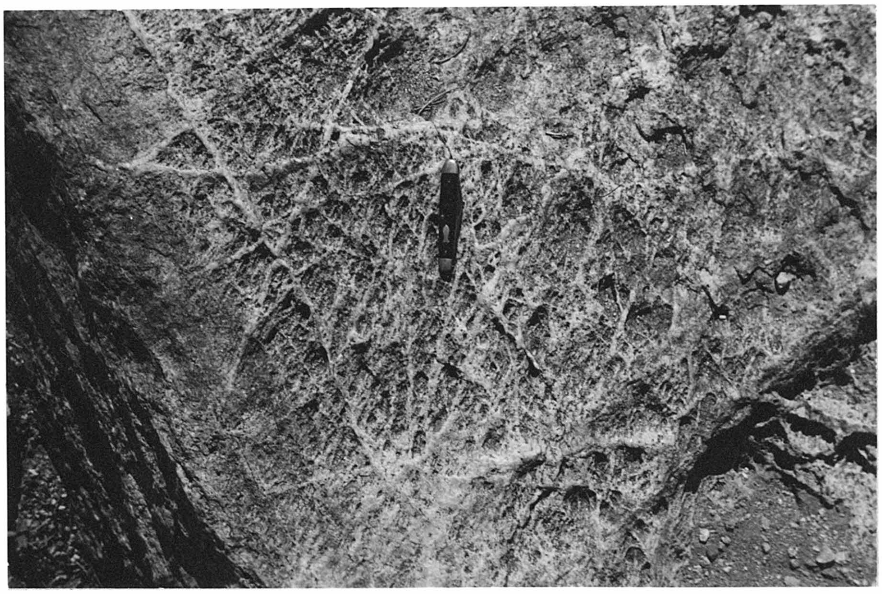


Figure 36 -- Intricate network of quartz-sulfide veinlets. Exposure in canyon bottom, west central part of S 24, T 23 N, R 18 W.

Figure 37 -- Branching and cross-cutting quartz-sulfide veinlets. Dark stains are limonite. Road cut, SE corner S 24, T 23 N, R 18 W.

grains in the rock and in veinlets, and this seems to be contemporaneous with quartz and pyrite.

Hydrothermal alteration -- The most obvious change caused by the mineralizing solutions was silicification of the rocks. The walls of veinlets are frequently impregnated with quartz, and several large areas were so effectively hardened by silica that they have eroded into rough, craggy peaks. Ithaca Peak represents such an area (See Figure 12), as do the peaks along the south side of the entrance to the Mineral Park basin (See Figure 38).

Sericite was formed almost as abundantly as quartz, and many rocks seem in hand specimen to consist entirely of quartz, sericite, and scattered grains of pyrite. Numerous specimens contain argillized feldspars, but much of this may be supergene in origin. Ferro-magnesian minerals have been completely removed from the strongly altered areas, and the rocks are now white to yellowish gray.

A specimen containing fresh sulfides, from the Ostrich shaft in Mineral Park, was examined in thin-section. This rock contains approximately 70 percent granular quartz and 30 percent sericite. Minor amounts of clay mineral are associated with the sericite and apparently formed contemporaneously with it. Rutile is present both as sagenite webs, and as crystals, which are commonly in clusters. In one place rutile was observed replacing sphene. Some of the quartz corrodes and is later than pyrite, and sericite replaces much early quartz. Late pyrite partly replaces some of the sericite.

Oxidation and secondary enrichment -- The highly pyritic mineralization has assured a potent supply of strongly oxidizing solutions. As a result the surface capping is largely devoid of sulfide minerals but contains abundant residual "limonite". The quantity of iron sulfate

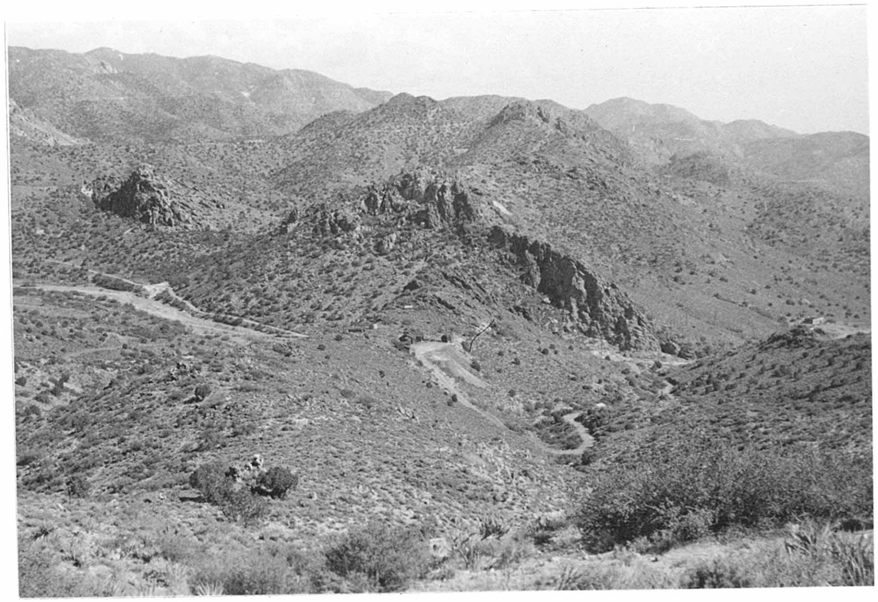


Figure 38 -- Rough crags of silicified rock, along south side of entrance to Mineral Park basin.

produced through oxidation of the pyrite is emphasized by the common occurrence of iron oxide-cemented talus and alluvium. Stream terrace deposits as much as 20 feet thick have been bound into dark reddish-brown breccia, and the bottoms of stream courses are in places covered with a cemented blanket of rubble a few inches to two feet thick. Examples of breccia are shown in Figures 39 and 40.

Oxide minerals of copper occur in a few places. Malachite is most common, staining oxide zone rocks. Small seams of malachite and azurite were seen in a few prospect pits. A specimen of breccia, collected near the mouth of a prospect tunnel in Bismark canyon, contains a cement of cuprite, native copper, and malachite. Arborescent plates of native copper were also collected from the dump of another tunnel in the same canyon. Iron-copper chalcanthite was observed on the walls of this tunnel.

A few polished sections show the development of supergene sulfides. In these sections chalcopyrite is surrounded by rims of covellite and chalcocite, and pyrite is replaced by chalcocite and minor amounts of covellite.

An indication of the depths of oxidation and secondary enrichment is given by the logs of three churn drill holes that were put down in the peak northeast of Gross ranch in 1915. The leached zone, which carried only traces of copper, was recorded to depths of 170, 180, and 290 feet. The "enriched" zone reached depths respectively, of 410, 520, and 340 feet.

<u>Age and genesis</u> -- The shattering and mineralization took place after the injection of the rhyolite dikes. The mineralization was a late geologic event but was the first phase of the general metallization of this region. It preceded the lead-zinc mineralization of the more

Figure 39 -- Dissected 30 foot terrace on south side of Bismark Canyon. Top 2-6 feet cemented by iron oxide. Ithaca Peak in left background.

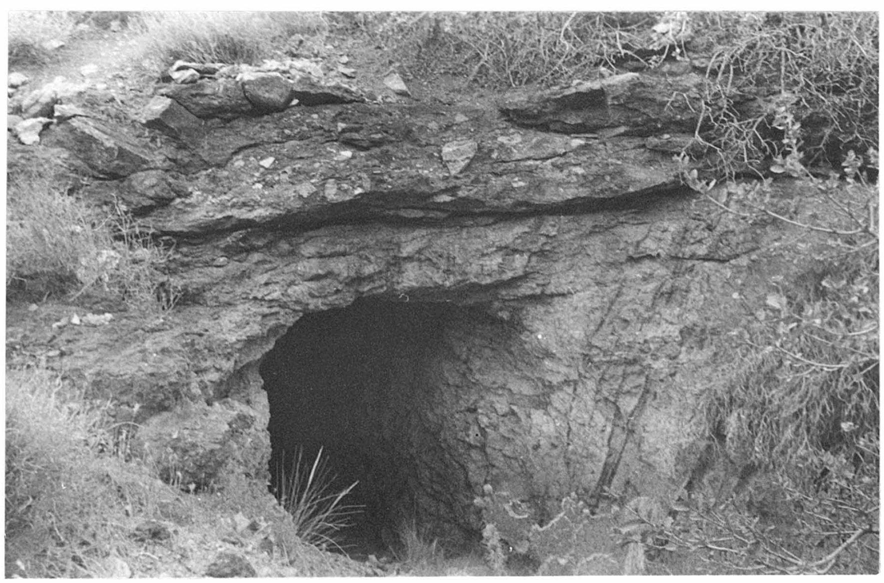


Figure 40 -- Layer of cemented talus overlying prospect hole. Bottom of canyon on east side of Ithaca Peak. Note mineralized fractures in bedrock.

widely distributed fissure veins, and it occupies a central position in the vein belt. Furthermore, the occurrence of sphalerite and galena in small veinlets intimately associated with the disseminated sulfides, suggests a close relationship between the two types of mineralization. Features pertaining to the origin and localization of the deposits have been discussed in a preceding section on ore genesis.

TURQUOISE DEPOSITS

Turquoise has been mined intermittently in the Mineral Park district apparently since pre-Columbian times, for stone implements and ancient Indian workings have been found on the south side of Aztec Mountain (Turquoise Mountain on Chloride quadrangle map). Deposits of turquoise have been exploited on both the south and north sides of Aztec Mountain, and on all sides, from top to botton, of Ithaca Peak. Minor workings occur in the ridge just south of the entrance to the Mineral Park basin.

Mode of occurrence -- Turquoise deposits are restricted to the intrusive stock of Ithaca Peak porphyry and occur within the altered and leached capping which overlies the deposit of disseminated sulfides. It is perhaps significant that the turquoise has formed in those portions of the capping that are most highly silicified and sericitized and which have eroded into rough peaks and ridges.

Turquoise is present mostly in seams and veinlets and commonly fills vugs and cavities in earlier quartz. Lenses and kidneys, with nodular surfaces, have formed in places in wide veinlets and within masses of sericite and clay mineral. Detailed descriptions of the grade and manner of occurrence of turquoise in the various claims have been given by Sterrett 116/. Associated minerals are those which would be expected to form from the hypogene alteration and disseminated sulfide mineralization of granite porphyry, followed by supergene leaching. The minerals include quartz, sericite, clay mineral, hydrous iron oxide, malachite, and chrysocolla. In a thin-section of a specimen from Ithaca Peak turquoise occurs as discontinuous veinlet segments, associated with what seem to be contemporaneous segments of goethite and jarosite.

All the workings are surficial in nature, and much of the mining has been open-cut methods. Narrow benches have been cut in many of the steep slopes of Ithaca Peak, and working faces as much as 50 feet high have been carried progressively back into the mountain.

Origin -- There is general agreement that turquoise is a mineral of secondary origin. It is variable in composition but is usually stated as $CuO.3Al_2O_3.\ 2P_2O_5.9H_2O$. Ball 117/ classes it as having formed by "descending oxidizing waters", and a convincing analysis by Paige 118/ leads to the conclusion that it is the result of supergene processes. Such an origin is compatible with the features of the Mineral Park deposits, for they are analogous to the deposits discussed by Paige. Their restriction to the leached "porphyry copper" capping is suggestive of a secondary origin, and the close association in time of turquoise, goethite, and jarosite is strong confirmatory evidence. The source of the necessary solutions and the probable chemical action involved have been discussed fully by Paige.

EMERALD ISLE COPPER DEPOSIT

The Emerald Isle copper deposit is located in the Sacramento Valley, half a mile from the west face of the mountains. It is approximately 3 miles south of the town of Chloride and 15 miles northwest of Kingman. Its geologic setting is an alluvium covered pediment, which in this area is cut in Ithaca Peak granite porphyry. The relief is low and undulatory, partly from initial irregularities in the pediment surface, which are expressed by protruding knobs and ridges of bedrock, but mostly from recent erosional dissection. The mine is on a northeast-trending low ridge which has an alluvial veneer of variable thickness. The general setting of the deposit is shown in Figure 41.

Nature of the deposit -- The deposit consists of a mineralized blanket of alluvium and a fissure vein. The vein cuts not only the granite porphyry bedrock but also the overlying alluvium. Minor fissures and veinlets occur parallel to the main vein and likewise extend from bedrock into alluvium. The principal copper mineral in both blanket and veins is chrysocolla. The resulting green color of the mineralized ground explains the appropriate name of the deposit.

Blanket mineralization -- Copper has been added to the blanket by the deposition of copper-silicate minerals in the pore spaces of the highly permeable alluvium. Dioptase ($CuSiO_3 \cdot H_2O$) has been reported as constituting several percent of the ore 119/, but the principal mineral seems to be chrysocolla ($CuSiO_3 \cdot 2H_2O$). The copper-silicate material ranges from pale blue-green to moderate blue green in color. Associated with this green material is a brittle shiny black substance that yields copper when reduced with soda and charcoal under the blow pipe. It is perhaps best classed as "copper pitch", though it might be a variety of

Figure 41 -- Emerald Isle mine, view looking east. Low ridge in immediate background is bedrock protruding out of alluvial blanket. West face of Cerbat Range in distance.

Figure 42 -- Open pit in copper-bearing alluvial blanket at Emerald Isle mine. View looking west.

chryscocolla. It is possible that much chrysocolla is composed of variable amounts of copper oxide, silica, and water 120/, and differences in color and properties are to be expected. The presence of impurities would also affect the nature of the mineral. "Chrysocolla" will be used here in a broad sense that will imply variations and also the presence of dioptase.

The chrysocolla forms a cementing matrix for the alluvial detritus. It occurs chiefly in the form of microscopic acicular crystals, packed into narrow vermiform bands. In places it forms hemispherical or spherical radiating groups. The texture is a delicate crustification type that could only form by deposition of successive thin layers. A minor amount of the chrysocolla is cryptocrystalline, which, at least in part, represents an early stage of deposition, for the acicular bands have formed upon, around, and intruding into the cryptocrystalline material. The open spaces in the alluvium were not everywhere completely filled, and the chrysocolla in some places has a finely botryoidal surface.

Scales and films of brown to black copper oxide are common on the surface of the chrysocolla. These may be earthy or have a distinct metallic luster and can be classed as either tenorite or melaconite.

The limits of mineralization in the alluvial veneer have not been determined, but an area in which the blanket contains an average of 1 to 2 percent copper has been blocked out by drilling. This has a roughly oval shape that trends about N 75 degrees E, is more than 1300 feet long, and 400 to 500 feet wide. The ore body in most places is 25 to 30 feet thick. Ore occurs at the surface in some places but for the most part is covered by an overburden of unmineralized or only slightly mineralized alluvium. The overburden is from a few feet to more than 90 feet thick but averages only about 15 feet. In some places ore extends to bedrock, in others it is underlain by less strongly mineralized alluvium. All the dimensions are assay limits and do not define the complete extent of mineralization.

Exposures in the open pit at the mine contain an assemblage of sand, gravel, cobbles, and boulders, which are poorly sorted but coarsely bedded. The strike of the bedding is approximately east and the dip 4 degrees south. The open pit exposure of the blanket is shown in Figure 42.

Vein mineralization -- The principal vein strikes N 30 degrees E, cutting through the mineralized blanket. In its uppermost portions the vein is vertical or dips steeply north, but dips of 45 degrees N have been reported in some of the lower workings. The vein varies from 3 to 12 feet in width. At and near the surface, alluvium occupies both walls. At depths as little as 25 feet, however, bedrock occurs in the footwall, adjacent to alluvium in the hanging wall. The amount of displacement was not determined.

Early development work at the mine was confined largely to the vein. Two short shafts were sunk and lateral underground workings are reported to total 1600 feet, chiefly at the 100 foot level 121/. An average copper content of 3½ percent is reported for all these workings and an average of 6½ percent for the main drift, which apparently was driven within the vein.

The mineralogy of the vein is identical with that of the blanket, and in a winze 40 feet below the 100 level the ore values were apparently still furnished by chrysocolla. In the upper portions of the vein the filling between the walls consists of cemented alluvium that is analagous to the adjacent blanket, except for a higher copper content. The walls are distinct, roughly rolling, show effects of shear, and in places are lined with small amounts of gouge. Seams of delicately banded chrysocolla characteristically line both walls, and other strong seams occur in the interior of the vein. An exposure of the vein, where it was encountered in open pit excavation, is shown in Figure 43.

Where bedrock was observed in the footwall the vein filling still consisted of cemented alluvial detritus. The nature of the vein where bedrock occurs in both walls is not known. Specimens of granite porphyry from the foot wall are leached and thoroughly altered, and tiny irregular veinlets of chrysocolla occur in the rock. In thin-section the principal minerals are seen to be abundant clay mineral, sericite, and brown chlorite.

Minor fractures -- In the south face of the open pit, as it existed in June, 1948, a zone of mineralized irregular fractures was exposed. This extended eastward from the main vein for 100 feet, at which point the pit walls were caved. These seams and veinlets were spaced from 1 to 10 feet apart, were all essentially vertical and had strikes roughly parallel to the main vein. Thirty-five feet east of the main vein a knob of bedrock was exposed at the bottom of the face, and the chrysocolla-filled fractures were observed to pass into the bedrock. Some of the veinlets showed slight displacements, but most seemed to be dilation fractures. Some extended to the surface, others died out upward.

Age and genesis -- The mineralization, occurring as it does in a blanket of alluvium and in a fissure vein that passes from a rock pediment into alluvium, is dated as Quaternary. There has been some recent dissection of the pediment area, but terrace levels in the mountains indicate that 50 feet would be a maximum for any former cover. If the deposit had formed prior to Quaternary time a thicker cover

<u>Figure 43</u> — Exposure of Emerald Isle vein in the west end of the open pit, Summer, 1947. View looking south.

would be expected, and the mountain front should have migrated farther back from the mineralized portion of the pediment.

It has been suggested that the mineralization was by solutions derived from the weathering of the "porphyry copper" deposits of the Mineral Park district. This would involve gravitative transfer of the solutions, and localized deposition around and within a strong fissure vein and associated fractures. Such solutions could exist, but the concentration of copper in them would be negligible, and there are no plausible reasons to explain the concentration and deposition of the copper at this particular location and within a vein.

On the other hand, solutions ascending along fissures and spreading out into the alluvium provide a simple and logical source for the copper. Assuming this to have happened, the question arises as to the nature of the chrysocolla. This mineral is usually supergene and is a secondary product of various primary copper-bearing minerals. In the Emerald Isle deposit, however, the following points suggest that the chrysocolla is primary:

1) There are no relict grains of sulfides, or any minerals, which might have served as a primary source of the copper. It might be assumed that replacement or solution of such primary minerals was complete, but at least a few specks should have been preserved here and there.

2) The texture of the chrysocolla, both in vein and blanket, is delicately banded and crustified. Formation was invariably by deposition and not replacement. This suggests that the source of copper was elsewhere, and if the chrysocolla is supergene the logical source would be at some higher level. If there were primary mineralization above, however, furnishing the source of copper solutions, there should have been primary

mineralization at the present levels, at least in the vein. This would have to be leached completely away, before the solution of overlying material, in order to explain the lack of relict primary minerals and replacement textures. Such a sequence does not seem feasible.

3) Some of the veinlets pinch out upward. The chrysocolla filling apparently was deposited by ascending solutions. Perhaps the veinlets could be explained by lateral secretion, but the primary source material would still be missing.

From the above considerations it is concluded that the mineralization has resulted from deposition of chrysocolla by ascending hypogene solutions, which rose along one large and many small fissures and spread out into the adjacent alluvium. The conclusion is supported by the fact that the deposit was formed under essentially surface donditions. The main fissure and some of the associated minor fractures undoubtedly reached the original surface. In such an environment ascending hypogene solutions would be under the same pressures and could very easily have the same temperatures as the supergene solutions that deposit chrysocolla. And there is no reason why copper and silica could not be present in the proper amounts to form chrysocolla from such hypogene solutions.

REFERENCES

1 Ransome, F.L., Geology of the Globe copper district, Arizona: U.S. Geol. Survey, Prof. Paper 12, p. 15, (1903).

2 Schrader, F.C., Mineral deposits of the Cerbat Range, Black Mountains, and Grand Wash Cliffs, Mohave County, Arizona: U.S. Geol. Survey, Bull. 397, p. 50, (1909).

3 Russell, R.J., Dry climates of the United States: Univ. of Calif. Publ. Geogr., vol. 5, p. 38, (1931).

4 Lausen, Carl, Geology and ore deposits of the Oatman and Katherine districts, Arizona: Ariz. Bur. Mines, Bull. 131, p. 11, (1931).

5 U.S. Dept. of Agriculture, Yearbook of Agriculture, p. 763, (1941).

6 Longwell, C.R., Geology of the Muddy Mountains, Nevada, with a section through the Virgin Range to the Grand Wash Cliffs, Arizona: U.S. Geol. Survey, Bull. 798, p. 2, (1928).

7 Marcou, Jules, in Explorations and surveys for a railroad route from the Mississippi River to the Pacific Ocean, 1853-54: War Department, vol. 3, part 4, p. 171 (1856).

8 Newberry, J.S., in Lt. J.C. Ive's report on the Colorado River of the West, part 3, pp. 29-54, (1861).

9 Wheeler, Lt. G.M., Preliminary report, explorations and surveys in Nevada and Arizona: War Department, pp. 53-54, (1872).

10 Loew, Oscar, in Geographical surveys west of the 100th. meridian, Appendix JJ of the annual report for 1876: War Department, pp. 55-56, (1876).

11 Lee, W.T., Geologic reconnaissance of a part of western Arizona: U.S. Geol. Survey, Bull. 352, pp. 23-24, 49-50, 52-53, (1908).

12 Schrader, F.C., <u>op cit</u> (Ref. No. 2)

13 Hernon, R.M., in Some Arizona ore deposits: Ariz. Bur. Mines, Geol. Series No. 12, Bull. 145, pp. 110-117, (1938).

14 Bastin, E.S., Origin of certain rich silver ores near Chloride and Kingman, Arizona: U.S. Geol. Survey, Bull. 750, pp. 17-39, (1924).

15 Bastin, E.S., Chemical composition as a criterion in identifying metamorphosed sediments: Jour. Geol. vol. 17, p. 455, (1909).

16 Goodspeed, G.E., Pre-Tertiary metasomatic processes in the south eastern portion of the Wallowa Mountains of Oregon: 6th Pacific Sci. Congress, Proc., p. 402, (1939).

17 Harker, Alfred, Metamorphism: Methuen, London, pp. 218, 286, (1932).

18 Harker, Alfred, *op cit*, p. 266.

19 Harker, Alfred, *op cit*, pp. 278-286.

20 Buddington, A.F., Adirondack igneous rocks and their metamorphism: Geol. Soc. Am., Mem. No. 7, pp. 267-282 (1939).

21 Campbell, Ian & Maxson, J.H., Geological studies of the Archean rocks at Grand Canyon: Carn. Inst. Wash., Year book No. 35, p. 330, (1936).

22 Schrader, F.C., *op cit* (Ref. No. 2) p. 29.

23 Fenner, C.N., The mode of formation of certain gneisses in the highlands of New Jersey: Jour. Geol. vol. 22, pp. 594-612; 694-702, (1914).

24 Turner, F.J., Mineralogical and structural evolution of the metamorphic rocks: Geol. Soc. Am., Mem. No. 30, p. 306, (1948).

25 Harker, Alfred, *op cit*, pp. 346-347.

26 Turner, F.J., *op cit*, p. 9.

27 Turner, F.J., *op cit*, p. 54.

28 Turner, F.J., *op cit*, p. 76.

29 Turner, F.J., *op cit*, p. 104.

30 Turner, F.J., *op cit*, p. 104

31 Haury, P.S., Examination of zinc-lead mines in the Wallapi mining district, Mohave County, Arizona: U.S. Bur. Mines, Rept. of Investigations No. 4101, p. 33, (1947).

32 Noble, L.F., The Shinumo quadrangle, Grand Canyon district, Arizona: U.S. Geol. Survey, Bull. 549, pp. 55-60, (1914).

33 Hinds, N.E.A., Researches on Algonkian formations at Grand Canyon National Park: Carn. Inst. Wash., Year book No. 34, p. 327, (1935).

34 Campbell, Ian and Maxson, J.H., Geological studies of the Archean rocks at Grand Canyon: Carn. Inst. Wash., Year book No. 37, pp. 359-360, (1938).

35 Noble, L.F., *op cit*, pp. 32-35.

36 Longwell, C.R., *op cit* (Ref. 6), p.22.

37 Wilson, E.D., Pre-Cambrian of Arizona basin ranges: 6th Pacific Sci. Cong., 1939, Proc. vol. 1, pp. 321-330, (1940).

38 Schrader, F.C., op cit (Ref. No. 2) p. 30.

39 Lausen, Carl, op cit (Ref. No. 4) pp. 44-46.

40 Schrader, F. C., op cit (Ref. No. 2) p. 34.

41 Lee, W.T., op cit, (Ref. No. 11) p. 14.

42 Lee, W.T., op cit (Ref. No. 11) p. 16.

43 Lausen, Carl, op cit (Ref. No. 4) pp. 27-36 & Plate 1.

44 George, W.O., The relation of the physical properties of natural glasses to their chemical composition: Jour. Geol., vol. 32, pp. 365-366, (1924).

45 Schrader, F.C., op cit (Ref. No. 2) p. 40.

46 Lausen, Carl, op cit (Ref. No. 4) pp. 37-39.

47 Schrader, F.C., op cit (Ref. No. 2) p. 41.

48 Lee, W.T., op cit (Ref. No. 11) p. 16

49 Lausen, Carl, op cit (Ref. No. 4) p. 39.

50 Noble, J.A., High-potash dikes in the Homestake Mine, Lead, South Dakota: Bull. Geol. Soc. Am., vol. 59, pp. 927-939, (1948).

51 Lee, W.T., op cit (Ref. No. 11) pp. 63-64.

52 Billings, M.P., Structural geology: Prentice-Hall, Inc., N.Y. pp. 116-119, (1942).

53 Sharp, R.P., Basin-range structure of the Ruby-East Humboldt Range, northeastern Nevada: Bull. Geol. Soc. Am., vol. 50, p. 902, (1939).

54 Ferguson, H.G. & Cathcart, S.H., Major structural features of some western Nevada ranges: Wash. Acad. Sci. Jour., vol. 14, pp. 376-379, (1924).

55 Sharp, R.P., op cit, p.905.

56 Schuchert, Charles, Paleogeography of North America: Bull. Geol. Soc. Am., vol. 20, pp. 464, 470, (1910).

57 Schrader, F.C., op cit (Ref. No. 2) p. 30.

58 Longwell, C.R., op cit (Ref. No. 6) p. 126.

59 Schrader, F.C., op cit (Ref. No. 2) p. 43.

60 Elsing, M.J., & Heineman, R.E.S., Arizona metal production: Ariz. Bur. Mines, Bull. 140, p. 95, (1936).

61 Haury, P.S., Examination of zinc-lead mines in the Wallapai mining district, Mohave County, Arizona: U.S. Bur. Mines, Rept. of Inv. 4101, p. 4, (1947).

62 Hernon, R.M., op cit (Ref. No. 13) p. 111.

63 Elsing, M.J. & Heineman, R.E.S., op cit (Ref. No. ~~57~~ 60) p. 73.

64 Minerals Yearbooks, U.S. Bur. Mines, (1934-1946).

65 Mineral Park Milling Co., (F.J. McEntee Jr., and D.F. Zlatnik), personal communication, (1948).

66 Bastin, E.S., op cit (Ref. No. 14) p. 35.

67 Bastin, Graton, etc., Criteria of age relations of minerals: Econ. Geol., vol. 26, pp. 561-610, (1931).

68 Bastin, E.S., Paragenetic relations in the silver ores of Zacatecas, Mexico: Econ. Geol. vol. 36, pp. 373-376, (1941).

69 Lindren, W., Mineral deposits, 4th edition: McGraw-Hill, Inc., N.Y., p. 122, (1933).

Newhouse, W.H., Time sequence of hypogene ore mineral deposition: Econ. Geol., vol. 23, p. 651, (1928).

70 Schwartz, G.M., Progress in the study of exsolution in ore minerals: Econ. Geol., vol. 37, pp. 363-364, (1942).

71 Krieger, Philip, Notes on an x-ray diffraction study of the series calcite-rhodochrosite: Am. Mineral., vol. 15, pp. 24-26, (1930).

72 Schrader, F.C., op cit (Ref. No. 2) p. 49.

73 Locke, Augustus, Leached outcrops as guides to copper ore: Williams & Wilkins Co., Baltimore, p. 64, (1926).

74 Boswell, P.F., & Blanchard, R., Oxidation products from sphalerite and galena: Econ. Geol., vol. 22, p. 424, (1927).

75 Bateman, A.M., Economic mineral deposits: John Wiley & Sons, Inc., N.Y., p. 245, (1942).

76 Blanchard, R., Leached derivatives of arsenopyrite and chromite: Econ. Geol., vol. 37, pp. 596-626, (1942).

77 Boswell & Blanchard, op cit (Ref. No. 7~~2~~4) p. 441.

78 Boswell & Blanchard, op cit (Ref. No. 7~~2~~4) pp. 424-431.

79 Boswell & Blanchard, op cit (Ref. No. 7~~2~~4) pp. 431-438.

80 Bastin, E.S., op cit (Ref. No. 14) p. 18.

81 Boswell & Blanchard, op cit (Ref. No. 74), p. 441.

82 Schwartz, G.M., Hydrothermal alteration of igneous rocks: Bull. Geol. Soc. Am., vol. 50, pp. 195-197, (1939).

Lindgren, W., op cit (Ref. No. 69), pp. 457-458.

83 Butler, B.S., Influence of the replaced rock on replacement minerals associated with ore deposits: Econ. Geol., vol. 27, pp. 1-24, (1932).

84 Ross, C.S. & Kerr, P.F., The kaolin minerals: U.S. Geol. Survey, Prof. Paper 165-E, pp. 157-158, (1930).

85 Graton, L.C. & Bowditch, S.L., Alkaline and acid solutions in hypogene zoning at Cerro de Pasco: Econ. Geol., vol. 31, pp. 655-667, (1936).

86 Sales, R.H. & Meyer, C., Wall rock alteration at Butte, Montana: A.I.M.E., Mining Technology, TP 2400, p. 14, (May, 1948).

87 Gillson, J.L., Granodiorites in the Pend Oreille district of northern Idaho: Jour. Geol., vol. 35, pp. 1-31, (1927).

88 Sahama, Th. G., On the chemistry of the mineral titanite: Bull. de la Commission geologique de Finlande, N:o 138, pp. 88-120, (1946).

89 Jaffe, H. W., Reexamination of sphene: Am. Min., vol. 32, pp. 637-642, (1947).

90 Graton, L.C., The hydrothermal depth-zones: in Ore deposits of the western states: A.I.M.E., Lindgren volume, p. 189, (1933).

91 Lindgren, W., op cit (Ref. No. 69), p. 170.

92 Lindgren, W., op cit (Ref. No. 69), pp. 578-579.

93 Graton, L.C., op cit (Ref. No. 90), pp. 187-189.

94 McKinstry, H.E., & Noble, J.A., The veins of Casapalca, Peru: Econ. Geol., vol. 27, pp. 519-520, (1932).

95 Garrett, S.K., in Some Arizona ore deposits: Ariz. Bur. Mines, Bull. 145, p. 118, (1938).

96 Wimer, W.C. & Hall, J.G., private report, (1941).

97 Sales, R.H., The localization of values in ore bodies and the occurrence of shoots in metalliferous deposits: Econ. Geol., vol. 3, p. 336, (1908).

98 McKinstry, H.E., Mining geology: Prentice-Hall, Inc., N.Y., pp. 305-306, (1948).

99 Garrett, S.K., op cit (Ref. No. 95), p. 110.

100 Newhouse, W.H., Openings due to movement along a curved or irregular fault plane: Econ. Geol., vol. 35, pp. 445-464, (1940).

101 Wisser, Edward, The environment of ore bodies: Trans. A.I.M.E., vol. 144, pp. 108-109, (1941).

102 Hernon, R.M., op cit (Ref. No. 13), p. 113.

103 Lindgren, W., op cit (Ref. No. 69), p. 204.

McKinstry, H.E., op cit (Ref. No. 98), pp. 201-207.

104 Emmons, W.H., Relations of the disseminated copper ore in porphyry to igneous intrusives: Trans. A.I.M.E., vol. 75, p. 807, (1927).

105 Peacock, Hollis, An outline of the geology of the Bingham district: A.I.M.E., Min.& Met., vol. 29, pp. 533-534, (1948).

106 Emmons, W.H., On the mechanism of the deposition of certain metalliferous lode systems associated with granitic batholiths: In Ore deposits of the western states, A.I.M.E., p. 327, (1935).

107 Hulin, C.D., Ore genesis and ore shoots: Eng. & Min. Jour., vol. 127, pp. 228-230, (1929).

108 Spurr, J.E., Diaschistic dikes and ore deposits: Econ. Geol., vol.34, pp. 41-48, (1939).

109 Loughlin, G.F., Comments on the origin and major structural control of igneous rocks and related mineral deposits: Econ. Geol., vol. 36, p. 692, (1941).

110 Hulin, C.D., Factors in the localization of mineralized districts: Mining Tech., A.I.M.E., T.P. No. 1762, (Jan. 1945).

111 Pennebaker, E.N., The Robinson mining district: in Ore deposits as related to structural features, Princeton Press, p. 130, (1942).

112 Anderson, C.A., Structural control of copper mineralization, Bagdad, Arizona: Mining Tech., A.I.M.E., T.P. 2352, p. 8, (March, 1948).

113 Pennebaker, E.N., op cit (Ref. No. 111) p. 131.

114 Butler, B.S. & Wilson, E.D., Clifton-Morenci district: in Some Arizona ore deposits, Ariz. Bur. Mines Bull. 145, p. 74, (1938).

115 Loughlin, G.F., op cit (Ref. No. 109), pp. 688-689.

116 Sterrett, D.B., Precious stones: U.S.Geol. Survey, Mineral Resources of the U.S., Part II, pp. 847-852, (1908).

117 Ball, S.H., The geologic and geographic distribution of precious stones: Econ. Geol., vol. 17, p. 584, (1922).

118 Paige, Sidney, The origin of turquoise in the Burro Mountains, New Mexido: Econ. Geol., vol. 7, pp. 388-391, (1912).

119 Hanley, H.R., Rolla, Missouri, personal communication, (1949).

120 Ford, W.E., Dana's textbook of mineralogy, 4th. ed.: John Wiley & Sons, N.Y., p. 686, (1932).

121 Mohave County Miner, Boulder Dam edition, Kingman, Ariz., (1929).