

University of Nevada

Reno

The thesis of Donald E. Ranta is approved:

Supergene Enrichment at the Betty O'Neal Mine,
Lander County, Nevada

Thesis advisor

Anthony J. Payne

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science
in Geological Engineering

by

Donald E. Ranta

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Supergene Enrichment at the Betty O'Neal Mine,

Lander County, Nevada

Introduction

The Betty O'Neal mine is located in the Lewis mining district 12 miles southeast of Battle Mountain, Nevada, in northern Lander County. The climate and topography of the district is typical of the central Great Basin with arid valleys and semi-arid mountain ranges having great relief. The mine lies between 5300 and 6200 feet of elevation above sea level on the northwest slope of the northern Shoshone Range. The basin and range fault system near the mine separates the valley fill to the northwest from bedrock surfaces to the southeast. In addition to the Betty O'Neal, the Dean, Pittsburg, Morning Star, and Starr Grove mines are also situated in the Lewis district.

The district lies in the upper plate of the Roberts thrust which, according to Gilluly (1965, p. 7), consists of at least 16,000 feet of siliceous clastics, chert, and volcanic rocks ranging in age from Late Cambrian to Middle Devonian. The direction of thrusting is generally conceded to be from west to east. Erosion near the Betty O'Neal mine has left an undertermined thickness of chert, quartzite, and greenstone (?) of Ordovician age. In most areas near the mine, these rocks presumably overlie a carbonate facies in an unexposed lower plate of Late Cambrian to Middle Devonian age (Gilluly, 1965, p. 7). Other rock units associated with the mine include quartz porphyry dikes, a quartz latite intrusive, and carbonaceous shale interbedded with siliceous clastics and chert. To the southwest, rocks of the upper plate of a second major thrust are

exposed on a spur (Gilluly, 1965). This second major thrust fault apparently transported Battle conglomerate and Antler Peak limestone from near Battle Mountain, where they are autochthonous, eastward to override the rocks of the earlier Roberts thrust.

The Betty O'Neal mine has over 24,000 feet of underground workings and was mined mainly for its silver content. The veins in the mine are classified as mesothermal silver-lead-zinc deposits of the quartz-tetrahedrite-galena vein type. Ore within the mine occurs in a surface oxidized zone, in a supergene enriched zone below a barren part of the oxidized zone, and in an unenriched protore zone.

The Lewis mining district lies within the most well-known mineral belt in Nevada--the Eureka-Battle Mountain mineral belt (Roberts, 1966, p. 56,61). This mineral belt trends northwest beginning near the White Pine mining district, White Pine County, Nevada, and continues northwesterly through the Eureka, Cortez, and Battle Mountain mining districts to name a few.

The investigations of the ore minerals from the Betty O'Neal mine was undertaken to determine whether or not supergene enrichment of the silver ores was an important factor, to evaluate the effect of physical and chemical variables on any supergene enrichment, to determine which of the hypogene vein minerals was the principal silver-bearer, and to draw any conclusions which suitably explain the secondary processes involved at the mine.

One of the earliest discoveries concerning the ores at the mine, which may eventually be of great significance in any future exploration of the mine, was that the most common sulfide in the ore is silver-bearing tetrahedrite, or freibergite. Reports of similar mines in many

of the other mesothermal silver districts in western Nevada invariably estimate tetrahedrite (freibergite ?) to be less abundant than other base metal sulfides and a relatively minor constituent of the ores, although it is reported to have provided most of the silver for secondary enrichment. Thus, the Betty O'Neal mine may have minable ore at depths that have not been affected by the processes of oxidation and supergene enrichment.

To clarify a common misconception in the literature, a few terms are defined. The processes of secondary enrichment--oxidation, solution, and redeposition--involve three types of minerals: (1) hypogene or primary minerals, (2) oxidized minerals which have undergone no appreciable downward movement in solution, and (3) supergene minerals which have been derived from the solution of hypogene and oxidized minerals and redeposited by descending solutions. This distinction, between "oxidized" minerals for those that are simply the pseudomorphous oxidation products of hypogene minerals, and "supergene" minerals for those which have been taken into solution, descended, and redeposited, is used throughout this paper.

The writer is indebted to Dr. Anthony L. Payne of the Mackay School of Mines for proposing the problem and providing several field trips to the Betty O'Neal mine for the purpose of collecting samples and becoming familiar with the geology. Many of the ideas presented in this paper have resulted from discussions with Dr. Payne. Others who were very helpful are H. F. Bonham, Dr. N. L. Archbond, J. J. Sjoberg, W. J. Tafuri, L. M. Hammond, R. B. Cummings, C. E. Shaffer, J. L. McGillis and J. C. Thompson. J. B. Murphy provided his excellent workmanship

in preparing the polished and thin sections for the study. To them the writer's sincere thanks are offered.

From the discovery of its ores in 1876, the major output for the Lewis mining district has been 188,373 short tons of silver, lead, copper, and gold ore valued at \$3,184,635. These estimates do not include numerous small shipments made by an unknown number of leasers. The metal output since 1876 is shown in the following table, compiled from Couch and Carpenter (1943, p. 74), from Burgess (1924, p. 2), and from the U. S. Bureau of Mines Mineral Resources of the United States, 1862-1931, and Minerals Yearbooks, 1932-1964.

Table 1 Major Production of the Lewis Mining District

| YEAR | ORE short tons | AVERAGE SILVER CONTENT PER TON OUNCES | TOTAL VALUE |
|-----------|-------------------|---|----------------|
| 1876-1919 | 12,421 | | \$622,804 |
| 1920 | 4,812 | | 69,552 |
| | *(4,812) | *(14.10) | |
| 1923 | 38,163 | | 536,569 |
| | *(38,160) | *(19.05) | |
| 1924 | 28,982 | | 371,705 |
| | *(28,982) | *(19.66) | |
| 1925 | 23,290 | | 372,379 |
| | *(23,290) | *(23.49) | |
| 1926 | 31,145 | | 466,828 |
| | *(27,716) | *(26.48) | |
| 1927 | 26,534 | | 409,639 |
| | *(26,314) | *(30.30) | |
| 1928 | 21,749 | | 317,397 |
| | ***(21,749) | ***(35.00) | |
| 1929 | 1,277 | | 20,451 |
| | | | |
| | 188,373 | | \$3,184,635 |

*[production from the Betty O'Neal mine]

**[estimated production from the Betty O'Neal mine]

History of the District

From the discovery of its ores in 1876, the major output for the Lewis mining district has been 188,373 short tons of silver, lead, copper, and gold ore valued at \$3,184,635. These estimates do not include numerous small shipments made by an unknown number of leasers. The metal output since 1876 is shown in the following table, compiled from Couch and Carpenter (1943, p. 74), from Burgess (1924, p. 2), and from the U. S. Bureau of Mines Mineral Resources of the United States, 1882-1931, and Minerals Yearbooks, 1932-1964.

Table 1 Major Production of the Lewis Mining District

| YEAR | ORE short tons | AVERAGE SILVER CONTENT PER TON ounces | TOTAL VALUE |
|-----------|-------------------|---|----------------|
| 1876-1918 | 12,421 | | \$622,804 |
| 1922 | 4,812 | | 66,552 |
| | *(4,812) | *(14.10) | |
| 1923 | 38,163 | | 536,889 |
| | *(38,150) | *(19.05) | |
| 1924 | 28,982 | | 371,705 |
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| | <hr/> | | <hr/> |
| | 188,373 | | \$3,184,635 |

*(production from the Betty O'Neal mine)

** (estimated production from the Betty O'Neal mine)

In the late 1880's gold was mined along with silver in the Pittsburg, Dean, and Morning Star mines (Vanderburg, 1939). The Starr Grove and Betty O'Neal mines have been valuable chiefly for their silver content.

The first production of the Betty O'Neal mine was recorded in 1880. In 1882 Burchard (1882) reported that the owners of the mine had sunk a shaft 160 feet which bottomed 156 feet horizontally from ore. The ore body was said to have contained ruby and wire silver assaying \$1000 per ton.

Later the same year the boiler exploded killing two men and causing the subsequent litigation to suspend operations (Palmer, 1924). Except for minor work done by leasers, the mine remained inactive until 1917 when L. W. Getchell optioned the property. An unsuccessful attempt to unwater the shaft and workings with inadequate equipment was later followed by a successful attempt by the man's son, N. H. Getchell. An examination of the workings gave evidence of valuable ore. Palmer reported that by 1922 ore had been developed sufficiently to warrant erection of a mill. For seven years the Betty O'Neal mine was amazingly productive. By 1928 the rapidly dropping price of silver and the near exhaustion of the developed ore shoots with little or no additional exploration caused the mine to be shut down. Within those seven brief years, the Betty O'Neal mine produced approximately 171,000 tons of ore having an average grade of 24.6 ounces of silver per ton with minor recovery of lead, copper, and gold. In 1927 the Betty O'Neal mine was the largest producer of silver in Nevada, and in 1928 it was the third largest (Mineral Resources, 1927, 1928).

Leasers again attempted to "high-grade" the mine, especially in

the 1930's. Within recent years an option on the property was obtained and exploration work to find new ore shoots is currently in progress.

It was not the writer's intention in visiting the mine to make a detailed study of the geology of the Lewis district. However, from the literature and from brief visits to the mine, an accurate description of the general geology can be made.

The Lewis mining district is believed to be underlain in part by an altered porphyry, possibly in the form of dikes emerging from a deep-seated igneous intrusion of batholithic proportions. Burgess (1926, p. 12) helps to substantiate this by stating that a large amount of porphyry unexposed underground on the south end of the Betty H'Neal mine workings dipped to the north. Furthermore, relatively small porphyry dikes near the surface in the upper part of the mine become larger and more numerous at depth. This is also true for the porphyry dikes seen in drill core from the mine area. At the surface, very little porphyry can be seen in the narrow outcrops because of the soft nature of the intensely altered dike rock.

Before the intrusion of the igneous rocks, the district had the typical Roberts thrust arrangement with "siliceous" or "volcanic" facies rock of early and middle Paleozoic age overlying and in thrust fault contact with "carbonate" or "sedimentary" facies rock of approximately the same age (Hilluly, 1965, p. 7). Hilluly estimated that the thickness of the chert, quartzite, argillite, graywacke, pillow lava and tuff, and minor limestone and shale comprising the siliceous facies of the upper plate had a total thickness of 16,000 to 25,000 feet. He also estimated that the carbonate facies of the lower plate had a total thickness of 6700 feet, consisting of dolomite, limestone, and other clastics.

General Geology

It was not the writer's intention in visiting the Betty O'Neal mine to attempt a detailed study of the geology in the Lewis district. However, from the literature and from brief visits to the mine, an accurate description of the general geology can be made.

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Before the intrusion of the igneous rocks, the district had the typical Roberts thrust arrangement with "siliceous" or "western" facies rock of early and middle Paleozoic age overlying and in thrust fault contact with "carbonate" or "eastern" facies rock of approximately the same age (Gilluly, 1965, p. 7). Gilluly estimates that the thickness of the chert, quartzite, arkose, graywacke, pillow lava and tuff, and minor limestone and shale comprising the siliceous facies of the upper plate had a total thickness of 16,000 to 38,000 feet. He also estimated that the carbonate facies of the lower plate had a total thickness of 6700 feet, consisting of dolomite, limestone, and minor clastics.

A second period of thrust faulting occurred in the district placing Battle conglomerate and Antler Peak limestone in contact with the underlying Valmy formation. Near the Betty O'Neal mine erosion has completely removed rocks brought there by the second period thrusting with the exception of a remnant to the southwest of the mine previously mentioned. An additional undetermined amount of erosion of the upper plate siliceous facies of the Roberts thrust in the vicinity of the mine has left surface exposures of three main rock units--chert, dark-gray quartzite, and greenstone (?). These rock units are part of the Ordovician Valmy formation which Gilluly estimates has a thickness of at least 12,000 feet and possibly as much as 30,000 feet. No evidence near the mine has given any clues to the position of the mine in this thick sequence. Gilluly's cross sections (1965, Plate 2) based on regional surface geology, show the base of the Roberts thrust to lie approximately 11,000 feet below the surface at the mine.

The mine workings and drill holes have failed to reveal the base of the thrust zone while encountering greater and greater numbers of porphyry dikes with depth. Thus, the writer believes that immediately beneath the mine area deep drilling would reveal that the lower plate carbonate facies and an unknown thickness of the upper plate of the thrust have been replaced or pushed aside by an igneous intrusive of intermediate composition, probably granodiorite since that is the most common intrusive rock type found in the mineralized belt across the Shoshone Range.

A good description of the genesis of ore in mesothermal silver-bearing veins in the central Humboldt Range, Pershing County, Nevada, was given by Jenney (1935, p. 72-73). He believed that the igneous

intrusive was a cupola of a batholith which underlies the range. The intrusion of the batholith caused fracturing of the overlying brittle rocks. As the batholith was crystallizing, mobile and volatile ions, including the base and precious metals, migrated to the surface of the cupola. In the case of the Betty O'Neal mine, porphyry from a similar batholith underlying the Shoshone Range in a partially liquid state intruded into fractures in the country rock prior to the migration of the mobile constituents. Crystallization and hydrothermal alteration of the porphyry dikes in the hypabyssal environment along with renewed deformation resulted in fracturing and a decrease in the volume of the porphyry leaving passageways for mineralizing solutions. The mineralizing hydrothermal solutions emanated from the surface of the cupola into the partly-filled fracture zones where deposits containing quartz, base metal sulfides, and the sulfosalts of silver began to precipitate.

As early as 1915, Hill (p. 25) recognized that the silver-lead-zinc deposits of an early period of mineralization in western Nevada were always associated with quartz monzonite or granodiorite intrusives.

Within the underground workings of the mine, a carbonaceous shale is often interbedded with the chert and quartzite in the vicinity of the veins. This shale does not outcrop at the surface because it is extremely soft and yields readily to erosion. What significance this bed would have on the precipitation of metals and sulfides from hydrothermal or groundwater solutions remains in doubt. Its high carbon content could possibly have produced a reducing environment.

Another episode of geologic significance near the mine was the movement of a quartz latite intrusive by faulting to its present position

west of the mine. Later block faulting of the basin and range type must have released deep-seated fluids from a high-pressure zone, because much of the quartz latite seems to have been altered by hot-spring solutions.

The bulk of the metal production of the Betty O'Neal mine has come from ore shoots within the Estrella vein. The Estrella vein is located along a pre-mineralization fault zone recognized by an abundance of gangue. The vein generally strikes $\pm 25-30^{\circ}E$ and dips 40° north. Before being mined out, the more productive parts of the vein varied in thickness from a few feet to 50 feet (Palmer, 1925, p. 432). In many parts of the vein, highly altered quartz porphyry forms part of the hanging wall.

The writer had little opportunity for field study of the detailed relationship of the vein to the wall rock and ore changes with depth. Also, at the time of the field work, the workings of the Betty O'Neal mine were only partly accessible. One recently observed relationship is that the Estrella vein does not outcrop (Fryer, 1957, p. 41). It is truncated to the west in its upper extent by the Yankee fault-vein. The Yankee fault is thought to be contemporaneous with mineralization and is exposed on the surface. It carries low values in silver but was rarely of major economic importance. This nearly-vertical fault crosses the Betty O'Neal mine area in a $\pm 25^{\circ}E$ direction, west of which stream activity has eroded little valuable ore. Thus, the major part of the mine's production has come from a relatively small segment of the Estrella vein west of the Yankee fault and between the 3771' and the 5234' levels. Burgess (1925, p. 18) states that the Estrella vein does not continue downward to the Mitchell Tunnel level, the main haulage level and the lowest workings in the mine. Instead, it was disintegrated into a mass of stringers of quartz and other sulfides, or, perhaps, be

Ore Deposits

The bulk of the metal production of the Betty O'Neal mine has come from ore shoots within the Estella vein. The Estella vein is located along a pre-mineralization fault zone recognized by an abundance of gouge. The vein generally strikes N 20-30°E and dips 45° west. Before being mined out, the more productive parts of the vein varied in thickness from a few feet to 55 feet (Palmer, 1924, p. 450). In many parts of the vein, highly altered quartz porphyry forms part of the hanging wall.

The writer had little opportunity for field study of the detailed relationship of the vein to the wall rock and the changes with depth. Also, at the time of the field work, the workings of the Betty O'Neal mine were only partly accessible. One recently observed relationship is that the Estella vein does not outcrop (Payne, 1967, p. 41). It is truncated to the east in its upper extent by the Yankee fault-vein. The Yankee fault is thought to be contemporaneous with mineralization and is exposed on the surface. It carries some values in silver but was rarely of major economic importance. This nearly-vertical fault crosses the Betty O'Neal mine area in a N 20°E direction, west of which known activity has produced little valuable ore. Thus, the major part of the mine's production has come from a relatively small segment of the Estella vein west of the Yankee fault and between the 5771' and the 5834' levels. Burgess (1926, p. 18) states that the Estella vein does not continue downward to the Getchell Tunnel level, the main haulage level and the lowest workings in the mine. Instead, it must disintegrate into a group of stringers of quartz and minor sulfides, or, perhaps, be

faulted off by the block faults so common to the mine area.

East of the Yankee fault, an extension of the faulted Estella vein, called the Kinkaid vein, outcrops with the same N 20°E strike and 45° west dip (Payne, 1967, p. 44). Undoubtedly, this part of the vein intersects the Yankee fault at depth. One part of this extension was stoped out to some depth, but the vein appears to narrow considerably, and the amount of stoping and the size of the dump would indicate that production was minor. The Betty vein is of lesser importance than the main part of the Estella. It is exposed on the surface, but supplied none of the production in the 1920's. The first discovery of ore in the early 1880's was made on the Betty vein, then called the Betty O'Neal vein.

The normal vein material in the Estella vein is coarse milk-white to light-gray quartz. The quartz is often massive or in crude comb structure containing scattered cavities lined with acicular and terminated crystals. The vein occasionally shows banding parallel to its walls and, in some places, is divided by thin partings of vein barite and wall-rock. There is no evidence of widespread replacement of the country rock, although it is sometimes included within the vein material. The quartz has crystallized in open spaces produced by faulting and by the decrease in volume of the quartz porphyry dikes. There is a little calcite with the quartz, but it is usually of microscopic size. The recognizable ore constituents, in decreasing abundance, are freibergite, galena, sphalerite, pyrite, chalcopyrite, native silver, and pyrargyrite. Other minerals are of infrequent occurrence and of minor value. As a whole, the quartz is not particularly rich in sulfides except for a few localities. The tendency of the sulfides is towards fine veinlets and

disseminated in bands parallel with the walls of the vein. Locally, freibergite with other sulfides and quartz inclusions may widen in massive zones two to three feet wide (Burgess, 1926, p. 10).

Upon close examination, brecciated fragments and recrystallized bands of wall-rock are found to be included in veins near the borders. Quartzite seems to be the most common wall-rock inclusion in the veins.

The richest exposed shoots of ore have been mined out, but, according to Palmer, the average of the mill heads ran about 20 to 25 ounces of silver per ton with a small amount of lead, gold, and copper recovered during concentration.

The veins in the Betty O'Neal mine are classified, using Lindgren's classification of ore deposits (Lindgren, 1933), as a mesothermal silver-lead-zinc deposit of the quartz-tetrahedrite-galena vein type. Ore within the mine occurs in the three following environments:

1. Near-surface oxidized zone contains silver chloride (cerargyrite), quartz gangue, and subordinate azurite and malachite as described by Palmer (1924); in this zone, insoluble silver chloride and other silver halides were residually enriched at and near the surface as erosion removed the gangue minerals. High-grade, surface-enriched "horn silver" ores mined in the early days of Nevada's silver camps usually added little to the value of the districts.
2. Supergene enriched zone below a barren part of the oxidized zone has native silver which formed on the surfaces of tetrahedrite grains and secondary pyrargyrite replacing pyrite; these parts of the veins are often extremely porous and permeable having cavities lined with acicular quartz, subhedral galena, masses of freibergite coated with secondary minerals, and interspersed sphalerite containing

minute amounts of exsolved chalcopyrite.

3. Protore zone beneath the zone of enrichment has the primary base metal sulfides and sulfantimonides occurring in fissures in the quartz gangue; the sulfides occur in massive intergrowths and in cavities similar to the ones described in (2.) but with no secondary minerals.

Visible wall-rock alteration at the Betty O'Neal mine is almost negligible with the exception of the quartz porphyry dikes. Quartzite and chert in the vicinity of the veins often look no different than rocks at some distance from the veins. Particles in the matrix of the quartzite, identified with a microscope, are intensely sericitized, but this alteration cannot be viewed megascopically. One thin section of the vein and wall-rock contact had minute specks of pyrite in the quartzite wall-rock indicating weak pyritization.

The quartz porphyry has been intensely altered mainly by sericitization and, possibly, also by argillization making it very unstable and prone to caving. Burgess (1926) had a number of thin sections made of the porphyry but did not definitely identify the type of alteration. He did recognize "light brown, bleached, micaceous remnants of what was originally biotite" and that the alteration was generally pervasive (1926, p. 7).

A few grains which showed a high silver content by microchemical test and had the correct physical properties, are believed to be pyrrhotite. These grains were found as minute specks in quartz (which appeared to be replacements).

Analysis by simple electrolytic spectrometry and fire assay methods indicate that pyrrhotite found in the Betty O'Neal mine has a silver content of 10.18, galena has 8.19%, sphalerite has 9.12%, and pyrite has

Mineralogy

A total of 20 polished sections and two thin sections of ores from the Betty O'Neal mine were carefully examined by ore microscopy. Numerous polished sections from similar mesothermal silver mines in Nevada were also examined. Minerals were identified by their optical and physical properties, etch reactions, microchemical tests, and, when necessary, x-ray diffraction patterns. Of particular interest were the textures, especially replacement textures, of each of the various minerals with respect to the others.

Hypogene mineralization--The primary minerals common to the ores in the Betty O'Neal mine are fairly simple consisting of sulfides and sulfantimonides. The principal hypogene sulfides are freibergite, galena, sphalerite, and pyrite listed in decreasing abundance. Chalcopyrite, bournonite, and pyrargyrite (?) are less common hypogene minerals. Chalcopyrite was exsolved in sphalerite grains, bournonite replaces galena and freibergite, and pyrargyrite (?) is believed to replace galena in one locality. Freibergite is the main silver-bearing mineral as determined by assay, spectrographic analyses, and x-ray diffraction. Although pyrargyrite is known to be of supergene origin near the oxidized zone, it may also be hypogene at depth. A few grains, which showed a high silver content by microchemical test and had the correct physical properties, are believed to be pyrargyrite. These grains were found as minute specks in galena in what appeared to be replacements.

Assays by atomic absorption spectrophotometer and fire assay methods indicate that freibergite found in the Betty O'Neal mine has a silver content of 10.1%, galena has 0.19%, sphalerite has 0.12%, and pyrite has

0.089%. A composite sample of the ore from the 5771' level in the No. 5 tunnel, where the Estella vein has been entirely stoped out except for a few pillars, had a silver content of 6.17%.

The silver content of the various minerals listed above is due to variation in composition and to microscopic inclusions of silver-bearing minerals which could not be completely eliminated. Chalcopyrite, bournonite, and pyrargyrite could not be isolated in enough quantity for assay, but microchemical tests indicate a high silver content for the pyrargyrite (?) and none for the chalcopyrite and bournonite.

Successive stages of hypogene mineralization were delimited by periods of deformation which caused fracturing (see Figure 3, p.22). A study of the paragenesis of the vein minerals in the mine is summarized in Figure 3. The study showed that an early period of mineralization deposited mainly massive quartz with barite lenses and veinlets and finely disseminated calcite and pyrite. This initial period of mineralization was part of Lovering's (1949) late barren stage of hydrothermal alteration. Following minor deformation, another stage occurred with the emplacement of veinlets of quartz and pyrite in the early productive stage.

The vein quartz, which was deposited throughout all periods of mineralization, was described in detail previously. Microscopic calcite occurs as euhedral crystals usually enclosed by quartz grains. Calcite not enclosed by other grains was probably dissolved or replaced. In some specimens calcite fills angular spaces between quartz crystals. Rhodochrosite was found with calcite in a few specimens. Barite was seen by Burgess (1926, p. 10) to occur in massive pods and lenses up to three feet thick. The writer found only one megascopic occurrence of barite

in the upper levels of the mine as a lens several inches thick. Much of the massive variety of barite has an abundance of impurities, but high-purity crystals can be found lining cavities.

Early pyrite is found as extremely fine-grained euhedral disseminations in the quartz gangue. The crystal forms vary from cubes to pyritohedrons to octahedrons. Late pyrite occurs with quartz in veinlets up to one-half inch wide. The pyrite is euhedral to subhedral in veinlets with grain size often greater than 2 mm. These grains are often found as subhedral inclusions within later sulfide minerals. In the 6115' level of the mine, secondary pyrargyrite replaces large grains of pyrite. The replacement in some grains is nearly total, and pyrargyrite is seen in cubic pseudomorphs of pyrite (see Figure 5, p. 29).

A third deformation was followed by a second major period of mineralization characterized by the appearance of base metal sulfides. Metasomatic replacements by successive sulfides have resulted in intergrowths with sharp grain boundaries. The first mineral to be deposited in this period was sphalerite ($(\text{Zn,Fe})\text{S}$), and occasionally sphalerite with minor chalcopyrite in exsolution textures. The sphalerite is usually brown to dark brown indicating a moderate iron content. It is rarely found in solid aggregates while often distributed as small grains intergrown with galena and freibergite (see Figure 1, p. 20). Sphalerite is considered to be the first base metal sulfide to form because it contains inclusions of quartz and pyrite which it partly replaces while often found included within larger grains of freibergite. Exsolved chalcopyrite (CuFeS_2) is found in typical exsolution textures in sphalerite usually along cleavage traces and as scattered minute specks.

Galena (PbS) is nearly contemporaneous with sphalerite, being only

slightly later and overlapping in time of deposition. It is intimately associated with freibergite, which has replaced part of the galena leaving it as islands in the freibergite. It contains inclusions of pyrite, quartz euhedra, and sphalerite. Few places are found in the mine which have galena as the dominant sulfide, freibergite being so much more ubiquitous. The one area examined by the writer, where freibergite is much less common than galena, has a few microscopic specks of hypogene (?) pyrargyrite (?) (Ag_3SbS_3) which replaced some of the galena. A more positive identification of the pyrargyrite could have been made if one of the grains was found in the polished section of that sample location.

Freibergite ($(\text{Cu,Fe,Zn,Ag})_{12}\text{Sb}_4\text{S}_{13}$) was the last of the major hypogene minerals to form and also the most abundant. It commonly replaces galena and, less frequently, sphalerite while containing inclusions of quartz, pyrite, sphalerite, and galena. It is positively identified, as differentiated from tetrahedrite, by x-ray diffraction, spectrographic, and ore microscopy techniques. Freibergite, having 10.1% silver content plus being the most abundant sulfide present in the mine, made a good hypogene ore when it formed in thick lenses and massive sulfide veins. Burgess (1926, p. 10) reported that it occurred in thicknesses of two to three feet in highly productive parts of the veins. In a few specimens, cerussite replaces freibergite along borders and embayments where galena has been completely replaced.

Other hypogene minerals reported to have been found in the Betty O'Neal mine are bournonite (PbCuSbS_3) and stibnite (Sb_2S_3), both as minor constituents. Bournonite is found as a few small grains which appear to be replacing galena and freibergite. The specimens examined by the writer contained no stibnite.

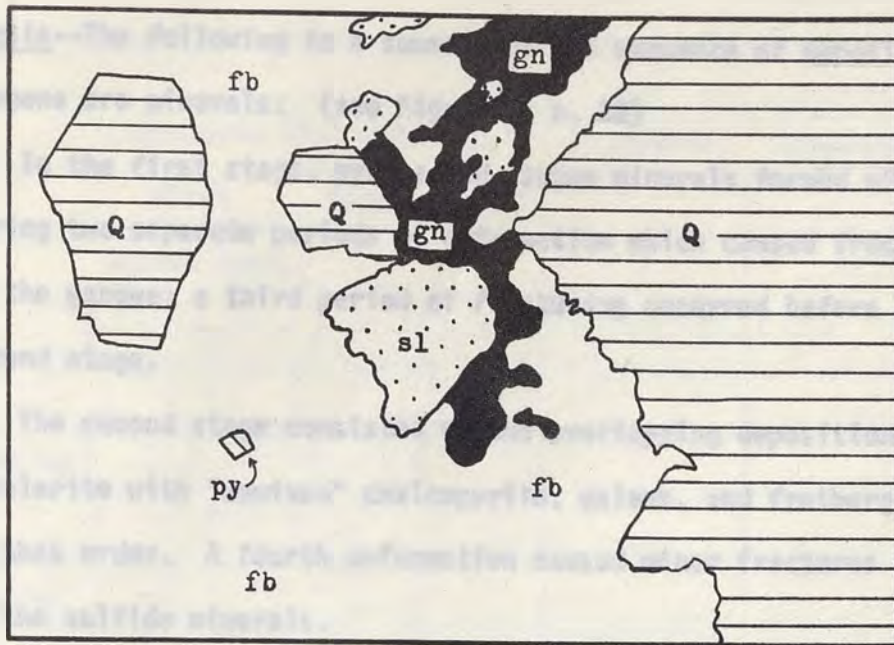


Figure 1 Characteristic intergrain boundaries in hypogene ore. Galena (gn); freibergite (fb); pyrite (py); sphalerite (sl); quartz (Q). Tracing from photomicrograph. 450 X

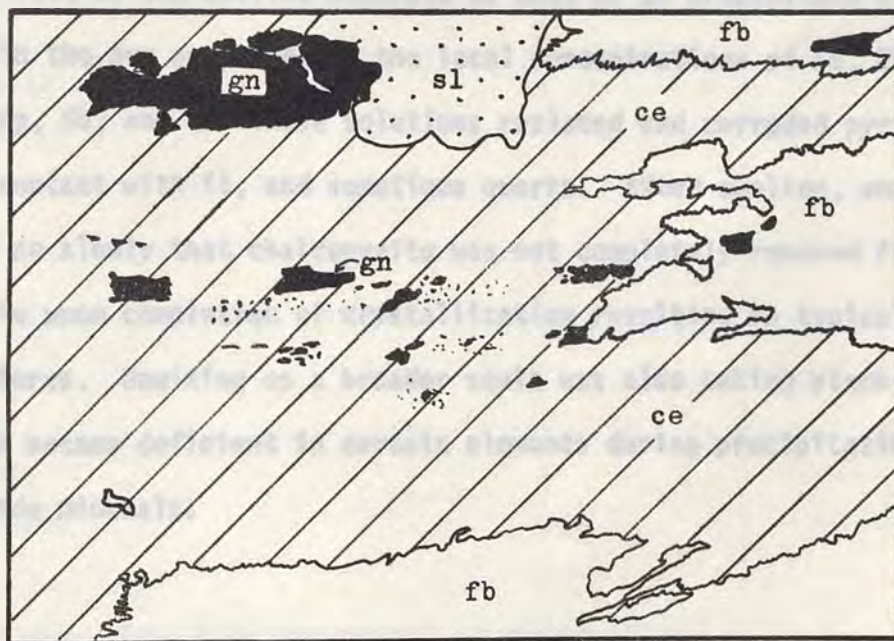


Figure 2 Textures of partly oxidized ore. Freibergite (fb) and galena (gn) partly replaced by cerussite (ce); sphalerite (sl). Tracing from photomicrograph. 450 X

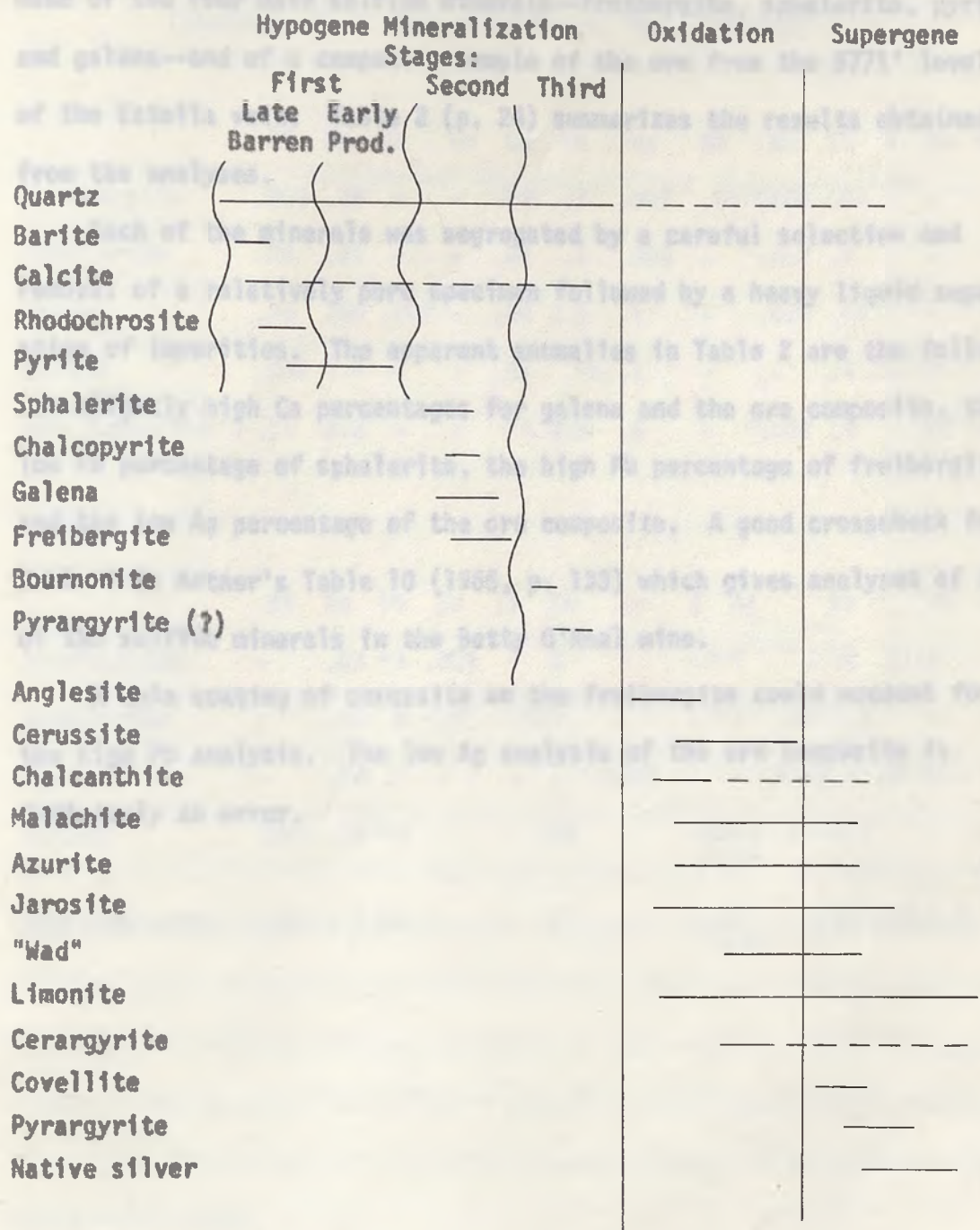
Paragenesis--The following is a summary of the sequence of deposition of the hypogene ore minerals: (see Figure 3, p. 22)

1. In the first stage, pyrite and gangue minerals formed after and during two separate periods of deformation which caused fracturing of the gangue; a third period of fracturing occurred before the second stage.
2. The second stage consisted of the overlapping deposition of sphalerite with "unmixed" chalcopyrite, galena, and freibergite, in that order. A fourth deformation caused minor fractures in some of the sulfide minerals.
3. The third stage consisted of the introduction of bournonite, pyrargyrite (?), and calcite. The calcite usually fills fractures in the earlier sulfides.

The role of the sulfide minerals as host or as precipitate varied locally in the ore according to the local concentrations of Fe, Zn, Cu, Pb, Ag, Sb, and S. These solutions replaced and corroded pyrite when in contact with it, and sometimes quartz. After cooling, unmixing occurred so slowly that chalcopyrite was not completely removed from the sphalerite upon completion of crystallization resulting in typical exsolution textures. Unmixing on a broader scale was also taking place as the solutions became deficient in certain elements during precipitation of the sulfide minerals.

(Vertical very thin fracture period of deformation.)

Figure 3 Paragenesis diagram of vein mineral development.



(Vertical wavy lines indicate periods of deformation.)

Ore composition analyses--Semiquantitative spectrographic analyses were made of the four main sulfide minerals--freibergite, sphalerite, pyrite, and galena--and of a composite sample of the ore from the 5771' level of the Estella vein. Table 2 (p. 24) summarizes the results obtained from the analyses.

Each of the minerals was segregated by a careful selection and removal of a relatively pure specimen followed by a heavy liquid separation of impurities. The apparent anomalies in Table 2 are the following: the slightly high Ca percentages for galena and the ore composite, the low Fe percentage of sphalerite, the high Pb percentage of freibergite, and the low Ag percentage of the ore composite. A good crosscheck for Table 2 is Katner's Table 10 (1965, p. 133) which gives analyses of some of the sulfide minerals in the Betty O'Neal mine.

A thin coating of cerussite on the freibergite could account for the high Pb analysis. The low Ag analysis of the ore composite is definitely an error.

TABLE 2
SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSES,
IN PERCENT, OF SELECTED MINERALS
(Analyst, U. S. Bureau of Mines, Reno, Nevada)

| | Al | Ca | Co | Cr | Cu | Fe | Mg | Mo | Ni | Si | B | Ba | Be |
|---------------|------|-----|------|----|-----|-------|------|-----|-------|-----|---|-----|----|
| Freibergite | .005 | .14 | - | - | >4 | .7 | .007 | .01 | <.002 | .04 | - | - | - |
| Sphalerite | .01 | .01 | - | - | .04 | .1 | .003 | - | <.002 | .2 | - | - | - |
| Pyrite | .08 | .50 | .007 | - | .04 | >>3.5 | .1 | - | .004 | .04 | - | - | - |
| Galena | .005 | 1.4 | - | - | .01 | .04 | .1 | - | - | .4 | - | - | - |
| Ore Composite | .01 | 3.6 | - | - | >4 | 3.5 | .6 | - | <.002 | .4 | - | .01 | - |

| | Bi | Mn | Pb | Sn | Ti | Zn | Zr | V | Ag | Sb | As | Au | Pt |
|---------------|------|-----|----|------|----|-----|-------|---|---------|---------|---------|----|----|
| Freibergite | - | .03 | >4 | .004 | - | 2 | - | - | >>>1 | >10 | .01-0.1 | - | - |
| Sphalerite | - | .60 | 2 | .4 | - | >>4 | - | - | >1 | .01-0.1 | - | - | - |
| Pyrite | - | .03 | .1 | - | - | - | .0075 | - | - | .01-0.1 | .01-0.1 | - | - |
| Galena | .005 | .10 | >4 | - | - | .08 | - | - | .01-0.1 | .01-0.1 | - | - | - |
| Ore Composite | .005 | 1.0 | >4 | - | - | 2 | - | - | .01-0.1 | >10 | 0.1-1.0 | - | - |

Oxidized minerals--Sulfates, carbonates, oxides, and chlorides all formed during the oxidation of hypogene and, possibly, supergene minerals. These minerals were oxidized when meteoric water rich in dissolved oxygen came in contact with sulfides. Later variations are due to the extent of further oxidation and the availability of certain ions and elements.

The first oxidized minerals to form are the sulfates. These would include anglesite (PbSO_4), jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$), and chalcantite ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$). Extremely small quantities of these minerals were found, and with the exception of anglesite, then, often as post-mining oxidation of exposed sulfides. Anglesite is seen in a few specimens, under high power of a microscope, as a thin coating separating galena from cerussite. It formed as an oxidation product of galena.

Amber yellow to yellowish-brown jarosite is exposed as small patches in drifts and stopes of the mine. It normally occurs as a complete or partial replacement of pyrite and sericite, and is abundant in areas of intense sericitic alteration and high pyrite content. Chalcantite is observed as coatings on freibergite. Jarosite and anglesite are found as pseudomorphous oxidized coatings on primary minerals, while chalcantite may or may not have undergone movement in solution and, thus, be supergene. Jarosite often forms when a solution containing iron and sulfate ions comes in contact with sericite which provides the potassium necessary for precipitation.

If carbonate ions (CO_3^-) are present in solution, the unstable sulfates are quickly replaced, converting to carbonates. Such is the case for cerussite (PbCO_3) which replaces anglesite, and for malachite ($\text{Cu}_2(\text{CO}_3)(\text{OH})_2$) and azurite ($\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$) which replace chalcantite.

Cerussite with minor anglesite occurs in a nearly total replacement of galena in a few specimens, and in a partial replacement of freibergite (see Figure 2, p. 20). Malachite and azurite are also found as coatings on freibergite. As is the case with the sulfates, the copper carbonates may be supergene while the lead carbonate is not.

Neither the sulfate nor the carbonate of zinc are found in the mine. This is probably due to the small amount of sphalerite in the ore and to the high solubilities of the oxidation products of zinc sulfide.

The only oxide minerals recognized in the mine are rust-brown limonite (a combination of hydrous oxides of iron) and black "wad" (manganese oxides). These minerals can also be of supergene origin. Limonite occurs as an end-product of the oxidation of pyrite and jarosite. Also, iron is often precipitated from solution replacing Cu^{++} and Ag^+ to form a supergene limonite pseudomorph. Manganese oxides result from the oxidation of rhodochrosite (MnCO_3), a very minor constituent of the gangue.

The last of the oxidized minerals to form was the chloride of silver, cerargyrite (AgCl). Cerargyrite or "horn silver" was not seen by the writer, but Palmer (1924, p. 450) reported that it was found in the near-surface oxidized zone along with malachite and azurite. It could have formed from the replacement of native silver or from the replacement of any silver mineral exposed to chloride ions near the surface under oxidizing conditions. If the movement of chloride ions in solution later helped to form cerargyrite, the mineral could be described as supergene. There is a good possibility that some of the other silver halides could be found in the same zone as cerargyrite.

Supergene minerals--The supergene minerals positively identified from the Betty O'Neal mine are covellite, pyrargyrite, and native silver. Each of these minerals is found as a lone replacement of primary minerals. A discussion of the criteria used for distinguishing supergene minerals from hypogene minerals is included in the section on "supergene enrichment".

Covellite (CuS) is recognized in one specimen as minute inclusions in cerussite and as a replacement of galena and freibergite. Much of the covellite appears to have been replaced by cerussite.

Supergene pyrargyrite occurs in the upper levels of the mine as a secondary replacement of pyrite (see Figure 4, p. 29). The replacement is nearly complete with only a few vestiges of pyrite remaining in many grains. Pyrargyrite attacked both the borders and interior of pyrite and is often in a pseudomorph of pyrite (see Figure 5, p. 29).

Native silver (Ag) is found in abundance in one of the drill cores of a newly discovered ore zone, and it is mentioned in some of the old reports of the mine. Native silver is found as finely curled wires extending into cavities from an attached base on the surface of freibergite grains. Native silver usually occurs in secondary replacement veinlets as the last mineral to form, but Edwards (1954) describes the occurrence and formation of native wire silver as a supergene mineral. A further discussion of the supergene processes which form native silver will be reviewed in the next section.

Minerals from the mine described as oxidized minerals which are also supergene include: chalcantite, malachite, azurite, jarosite, "wad", limonite, and cerargyrite. Malachite and azurite are seen replacing minute inclusions of calcite in one specimen from the oxidized zone.

Other minerals reported to have been found at the Betty O'Neal mine but not seen by the writer are argentite (acanthite ?) (Ag_2S), stephanite (Ag_5SbS_4), and polybasite ($\text{Ag}_{16}\text{Sb}_2\text{S}_{11}$). These are all silver minerals which may be either hypogene or supergene.

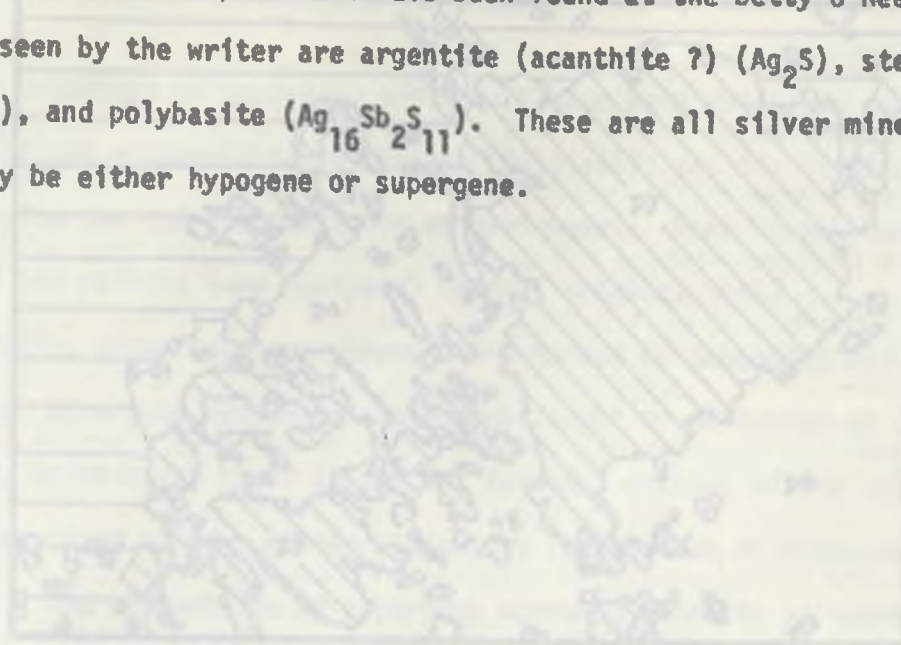


Figure 4. Textures of supergene replacement. Incomplete replacement of pyrite (py) by pyrargyrite (ps); quartz (qtz). Tracing from photomicrograph. 450 X.



Figure 5. Textures of supergene replacement. Complete replacement of pyrite (py) by pyrargyrite (ps); quartz (qtz). Tracing from photomicrograph. 450 X.

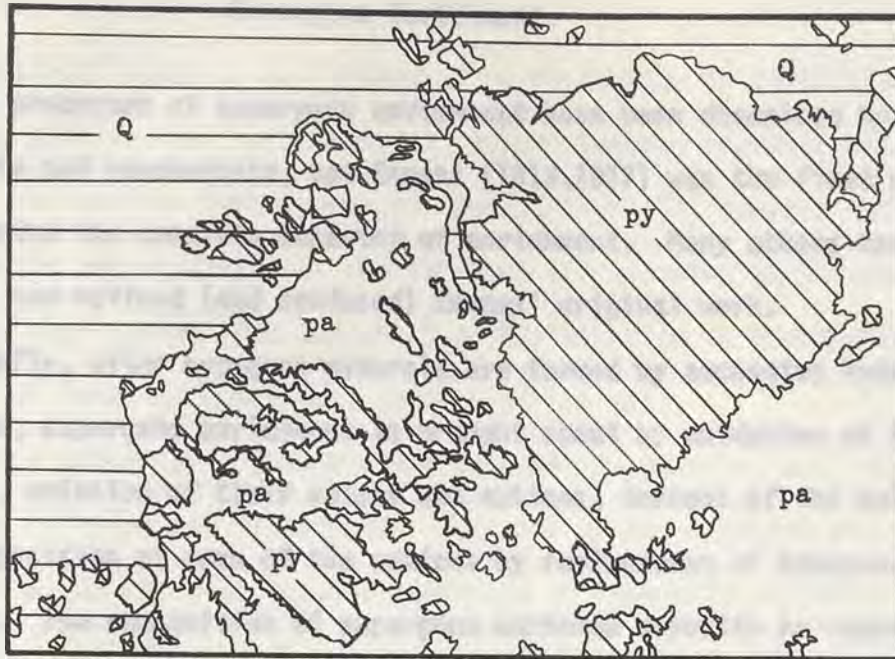


Figure 4 Textures of supergene replacement. Incomplete replacement of pyrite (py) by pyrrargyrite (pa); quartz (Q). Tracing from photomicrograph. 450 X

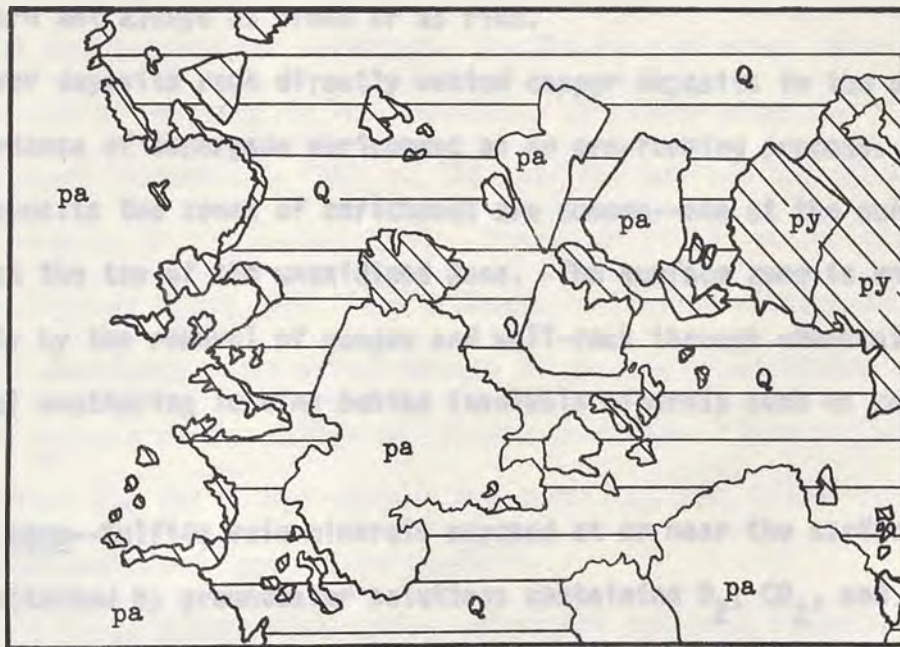


Figure 5 Textures of supergene replacement. Complete replacement of pyrite (py) by pyrrargyrite (pa); quartz (Q). Tracing from photomicrograph. 450 X

Supergene Enrichment

The processes of supergene enrichment have been described by many geologists and geochemists, but Emmons (1913,1917) was the first person to summarize the complete behavior of enrichment. Many others have since modified and refined (and confused) Emmons' original work.

Briefly, after hypogene minerals are formed by ascending hydrothermal solutions, supergene enrichment is brought about by oxidation of these minerals, solution of their anions and cations, descent of the solution, and redeposition of some of the cations by replacement of hypogene sulfides. The recognition of supergene enriched deposits as opposed to hypogene deposits is extremely important. Deposits with strong supergene enrichment often are the shallow, blanket type having submarginal ores at depth while hypogene deposits often extend to depth with good ore but are not always as broad or as rich.

Silver deposits rank directly behind copper deposits in the amount and importance of supergene enrichment as an ore-forming process. In silver deposits two zones of enrichment are common--one at the surface and one at the top of the unoxidized zone. The surface zone is enriched residually by the removal of gangue and wall-rock through chemical and mechanical weathering leaving behind insoluble minerals such as cerargyrite.

Oxidized zone--Sulfide vein minerals exposed at or near the surface are usually attacked by groundwater solutions containing O_2 , CO_2 , and H_2O during chemical weathering. Oxidation of pyrite followed by dissolving of the iron sulfate in groundwater causes the formation of dilute sulfuric acid. Such an aqueous solution acts as a powerful solvent for

many of the vein and wall-rock constituents.

Krauskopf (1965, p. 1) believes that the sulfur in sulfides while oxidizing goes to free sulfur and SO_2 before forming the sulfate ion ($SO_4^{=}$). The cations then do one of three things: (1) convert into compounds which are insoluble at the surface, (2) dissolve in the surface water and are removed from the area, or (3) dissolve in groundwater and are carried into the unoxidized portion of the vein.

Silver minerals in the oxidized zone of ore deposits are found in all three of the above situations. When any of the halogens are present, silver minerals would be rapidly converted to insoluble halides, or, if dissolved, precipitate from solution as silver halides. The source of halogens near the Betty O'Neal mine would most likely be the nearby playas. Strong winds could carry halide salts as dust-sized particles to the vicinity of outcropping veins where the halides would be dissolved in surface and groundwater solutions. In the case of mines where the concentration of halogens is low, oxidation of silver minerals in a low Eh environment (Krauskopf, 1965, p. 16) near the surface has resulted in the formation of the native metal. Krauskopf (1965, p. 9) maintains, from calculations using solubility products, oxidation potentials, and ionization constants, that silver should be readily precipitated as a halide or reduced to the native metal upon oxidation. This explains why native silver and the silver halides are often the only silver minerals found in the oxidized zone of ore deposits.

At the Betty O'Neal mine native silver has not been found in the upper oxidized zone while cerargyrite and the copper carbonates are fairly common there (Palmer, 1924). Near-surface conditions at the time of oxidation can be interpreted as having: oxidizing conditions, high

Eh, because silver would have been reduced to the native metal if the Eh was low; fairly high concentration of chlorides, but not enough to impede some downward migration of silver ions; high concentration of carbonates to prevent the downward migration of much of the copper; and a high pH resulting from the oxidation and solution of pyrite.

In mesothermal silver mines such as the Betty O'Neal, the near-surface enriched zone overlies a leached zone also thoroughly oxidized but barren of any minable ore. The leached zone had little or no chloride ion circulation. While chloride ions were restricted to the surface, the solution and downward movement of silver was not inhibited in the lower part of the oxidized zone. The majority of the oxidized and dissolved material is dissipated, but a small part of it descends in solution and is reprecipitated.

Supergene zone--Below the barren part of the oxidized zone is a secondarily enriched zone where metal cations in descending solutions are redeposited by replacement of primary sulfide minerals. Reducing conditions (low Eh at and immediately beneath the water table) neutralize the acid solutions causing the metallic ions to react with the sulfides and replace them. An important fact to remember is that the level of the water table during the time of enrichment may not resemble the present-day water table. Replacement textures and other criteria clearly indicate that the secondary gangue minerals are of a later generation than the host primary sulfides.

The common supergene silver sulfides are argentite (acanthite ?), pyrargyrite, and proustite (Ag_3AsS_3). Freibergite, when oxidized and dissolved, provides all the necessary elements for the secondary precipitation of pyrargyrite. In the Betty O'Neal mine, the plenitude of

freibergite and the presence of an oxidized zone overlying ore should have been conducive to the formation of at least moderate quantities of supergene pyrargyrite or the other silver sulfantimonides. Surprisingly little pyrargyrite, or sulfantimonides of silver, are found in the ore. This leads the writer to believe that the supergene processes at the mine were not as active as those reported in many other similar deposits in western Nevada.

Native silver is also formed by the supergene process. Ag^+ is more easily reduced than Cu^{++} (Krauskopf, 1965), so native silver should be, and is, relatively more important to supergene enriched silver deposits than native copper is to supergene copper deposits. Other silver minerals which can be both hypogene and supergene are the following: stephanite, polybasite, pearceite ($(\text{Ag,Cu})_{16}\text{As}_2\text{S}_{11}$), miargyrite ($\text{Ag}_2\text{S}\cdot\text{Sb}_2\text{S}_3$), dyscrasite (Ag_2Sb), and stromeyerite ($(\text{Ag,Cu})_2\text{S}$).

Cooke (1913) proposed an equation whereby an increase in ferric ions in solution would increase the solution of silver and an increase in ferrous ions would favor its precipitation. Actually, the oxidation state of the iron cations has less effect on silver ions than does the Eh of the solution. The Eh is particularly significant in the reducing environment of a water table where Fe^{+++} converts to Fe^{++} , and Ag^+ converts to native silver or silver compounds.

Native silver is an important constituent of part of the ore in the Betty O'Neal mine. A recent vertical drill hole intersected a vein assaying over 55 ounces of silver per ton. The core contains an abundance of native wire silver with a partly coiled, thread-like appearance.

Edwards (1954, p. 7-8) states that wire silver can form in the four following environments: (1) from the breakdown of silver sulfide (Ag_2S)

upon heating above 75°C, (2) from the breakdown of silver sulfide immersed in an aqueous solution of copper sulfate and ferrous sulfate, (3) from a solution of potassium antimonyl tartrate and silver sulfate at 130°C precipitating silver on the surface of a silver sulfide, and (4) from antimony-bearing solutions of silver sulfate at 130° depositing wire silver on the surfaces of minerals containing the base metals.

"The growth of the 'wires' takes place at their 'roots'," according to Edwards (1954, p. 8). Native silver is deposited at the attached base of the thread or wire. Chrysotile asbestos and other fibrous silicate minerals grow in a similar manner.

At the Betty O'Neal mine, the wire silver is attached to the surfaces of freibergite grains indicating that the fourth environment would most likely approximate the conditions at the mine. In the study of the ore minerals, supergene wire silver seemed to be as rare as pyrargyrite, the only other supergene silver mineral. The native silver came from one of the drill holes at a depth of 130-135 feet from the surface on the faulted extension of the Estella vein, and the pyrargyrite was found in the No. 1 Tunnel at a depth of about 38 feet from the surface also on the extension of the Estella vein (Payne, 1967, Figure 10). No known supergene enrichment occurs below the drill hole intersection of the wire silver, although oxidation reaches depths of 200 feet.

Criteria of supergene enrichment--Textural criteria used in determining hypogene versus supergene replacement have definite limitations. Bastin (1950, p. 52) states that textures of "replacement patterns are identical in hypogene and supergene replacements". Replacements along cleavages, boundaries, or fractures are essential prerequisites for supergene enrichment, however, other evidence has to be used along with textures

to positively identify supergene replacements.

The criteria for identifying supergene enrichment described by Bastin and used in this paper, with a few minor changes, are the following:

1. Oxidized zone minerals involved in chemically inconsistent or nonhomogeneous replacements, e.g. "limonite" (hydrous oxides of iron) replacing covellite (CuS), give a good indication of oxidation and movement of solutions, which are both necessary for enrichment. Bastin (1950, p. 53) places the oxidation of galena to anglesite and cerussite in the category of supergene replacement, but the writer believes that this simple replacement is more correctly termed "oxidation" rather than "supergene".
2. Successive replacements by one mineral at a time would be typical of the supergene process, whereas, simultaneous replacement by two minerals would be more common to hypogene mineralization.
3. Certain minerals are known to be often of supergene origin; others are known to be always hypogene. Combining this knowledge with other criteria would add to the argument for or against enrichment.
4. The limitation of important replacements in ore to shallow or moderate depths is characteristic of supergene origin.
5. Analyzing the gross economic aspects of a deposit, if a zone of high-grade ore is found immediately below a barren zone, and if at a moderate depth below the high-grade zone the value of the ore gradually decreases, the ore body has the bulk characteristics of enriched deposits.

Relating the ores at the Betty O'Neal mine to the preceding criteria definitely establishes the presence of supergene enrichment at the mine.

The oxidized zone minerals have not been extensively examined mainly due to the inaccessibility of part of the workings. The primary vein minerals at the mine have supergene minerals replacing them as seen in typical secondary textures. The replacements of the sulfides are by one mineral at a time. Native silver and covellite are universally known to be supergene rather than hypogene in western Nevada silver deposits, and they are found fairly close to the surface. Pyrargyrite can be either hypogene or supergene, but the replacement of pyrite by pyrargyrite occurring near to the surface and not found in any other location in the mine indicates a supergene origin.

by Coombs, 1939), and the Snake River district, Lander County (Foss, 1923; and Hill, 1915). (see Table 2, p. 41)

Hill (1915), Ferguson (1923), and York (1944) made generalizations about western Nevada mesothermal silver deposits which have the following characteristics:

1. well-defined massive quartz veins filling fractures,
2. primary sulfide, sulfosulfide, and sulfarsenide minerals,
3. close association to quartz monzonite or granodiorite intrusions,
4. well-marked alteration not readily visible except for sericitization of dikes and relative country rock,
5. distinct zones of oxidation, supergene enrichment, and pyrite,
6. usually subvertical ore when not enriched,
7. country rock composed of felsic igneous rocks.

Ferguson went on to explain that supergene enrichment is not important in late Tertiary epithermal deposits because of their lower content of pyrite, lower degree of permeability, and the impossibility of early and middle Tertiary conditions so common to the older mesothermal deposits.

Comparison with Other Districts

Numerous mines, prospects, and district throughout western Nevada have mesothermal silver-lead-zinc deposits, and a fair percentage of these are of the quartz-tetrahedrite-galena vein type. Since it would be impossible to describe all of them in detail, three of the more well-known districts were chosen which have been described in detail with respect to supergene enrichment. The three districts are: the Rochester district, Pershing County (Knopf, 1924); the northeastern Humboldt Range, Pershing County (includes the Arizona, Sheba, and De Soto mines described by Cameron, 1939); and the Reese River district, Lander County (Ross, 1953; and Hill, 1915). (see Table 3, p. 41)

Hill (1915), Ferguson (1929), and York (1944) made generalizations about western Nevada mesothermal silver deposits which have the following characteristics:

1. well-defined massive quartz veins filling fractures,
2. primary sulfide, sulfantimonide, and sulfarsenide minerals,
3. close association to quartz monzonite or granodiorite intrusives,
4. wall-rock alteration not readily visible except for sericitization of dikes and reactive country rocks,
5. distinct zones of oxidation, supergene enrichment, and protore,
6. usually submarginal ore when not enriched,
7. country rock commonly of Paleozoic sediments.

Ferguson went on to explain that supergene enrichment is not important in late Tertiary epithermal deposits because of their lower content of pyrite, lower degree of permeability, and the impossibility of early and middle Tertiary enrichment so common to the older mesothermal deposits.

Rochester district--The ore deposits at the Rochester mining district have been described by Knopf (1924) as quartz veins and stockworks with finely disseminated supergene argentite as the main silver mineral. Other sulfides present in small quantities are pyrite, sphalerite, galena, tetrahedrite (freibergite ?), covellite, and chalcopyrite. Knopf (1924, p. 46) states that "the tenor of the silver ores of the Rochester district depends largely, if not wholly, on their content of argentite."

When the Rochester district first began production shortly after 1912, the ore averaged between 30 and 60 ounces of silver per ton, and as mining continued deeper the grade of ore gradually decreased to 10 to 12 ounces per ton. The reason for this decrease is that supergene argentite replaced sphalerite to a large extent at and immediately below the former water table. Little of the silver in solution was able to descend more than a few hundred feet before being precipitated by reaction with sphalerite in the reducing environment. Thus, the ore is impoverished at depth and the grade increases upward to the water table. Knopf also concludes that the source of the silver for enrichment is from the sparse primary tetrahedrite.

Northeastern Humboldt Range--Silver deposits in the northeastern Humboldt Range are principally found at the Arizona, Sheba, and De Soto mines in bed veins, fissure veins, and stockworks (Cameron, 1939). The main hypogene sulfides are pyrite, arsenopyrite, sphalerite, galena, freibergite, and jamesonite, of which galena, freibergite, and jamesonite are the silver-bearing minerals. The principal supergene minerals are argentite, which replaces freibergite, and native silver, which is both introduced as the native metal and a direct oxidation product of silver-bearing sulfides.

Cameron (1939, p. 610) believed that "at least in most of the deposits supergene enrichment of lean protore has been the factor delimiting profitable from unprofitable ore." The Arizona mine had a decrease in grade of silver with depth below a zone of enrichment. The Sheba-De Soto deposit is probably very similar to the veins at the Betty O'Neal mine. Production from the deposit in the 1860's and 70's was mainly from hypogene freibergite and some supergene native silver (Cameron, 1939, p. 611).

Reese River district--The hypogene ore deposits of the Reese River mining district are fissure fillings of quartz and subordinate sulfides, sulfantimonides, and sulfarsenides in a quartz monzonite stock (Hill, 1915, and Ross, 1953). Hill believed that pyrargyrite was the most abundant secondary silver mineral and was often found replacing tetrahedrite. Polybasite was thought to be a secondary mineral filling quartz-lined drusy cavities, but in this association it is more likely a late hypogene mineral. Argentite, proustite, and stephanite are other secondary silver minerals reported by Hill.

At shallow depths from the surface, silver chlorides, silver bromides, and native silver were mined in the early days of the district. Below the surface ore zone is a narrow barren zone which was oxidized and leached. Ross (1953) thought that all of the minerals in the unoxidized part of the deposit were hypogene with the exception of minor quantities of argentite, chalcocite, and covellite. A photomicrograph (p. 60, Figure 12) appears to confirm that at least part of the proustite is definitely hypogene.

Of the three districts described above, the Sheba-De Soto deposit most closely resembles the silver-bearing veins at the Betty O'Neal mine.

The Sheba and De Soto mines reportedly produced, for the main part, hypogene sulfide ore, particularly freibergite, with some native silver. Thus, it would appear that supergene enrichment was not an all-important factor in the value of the ores. Other similarities are that the ores from the Betty O'Neal, Sheba, and De Soto mines are partly oxidized, contain minor amounts of chalcopyrite, pyrargyrite, stibnite (?), and gold, contain a little supergene covellite, and are difficult to evaluate as to the importance of enrichment.

The Rochester district and the Betty O'Neal mine have identical hypogene minerals, but the main supergene minerals for the former is argentite and for the latter native silver and pyrargyrite. The amounts of native silver and pyrargyrite, however, are very small. Also, freibergite or silver-bearing tetrahedrite at the Betty O'Neal mine is the most common sulfide, whereas, at Rochester tetrahedrite which supplied most of the silver for eventual enrichment is sparse and rarely visible to the naked eye, sphalerite being much more common.

The silver deposits at the Reese River district are complex and confusing. Other than the occurrence of surface, residually-enriched silver chloride ores in both the Reese River district and the Betty O'Neal mine, they have very little in common. The differences are probably due mainly to the great difference of the wall-rocks and their effect on the deposition of the ore deposits.

TABLE 3 GEOLOGIC SUMMARY OF DISTRICTS

| District | Country Rock | Age of Country Rock | Age of Ore Deposit | Wall-rock Alteration | Characteristic Gangue | Minerals and Ore |
|---|---|---|---|--|--|--|
| Lewis (Betty O' Neal mine) | chert, quartzite greenstone, minor shale, and quartz porphyry | Ordovician, (part of upper plate of Roberts thrust) | early Tertiary | sericitized quartz por., sediments appear unaltered | quartz barite calcite rhodochrosite | freibergite galena sphalerite pyrite chalcopryite native silver pyrargyrite |
| Rochester | rhyolite and trachyte | late Paleozoic or Triassic | early Tertiary and possible late Cretaceous (?) | silicification near veins, sericitization further away | quartz, tourmaline | covellite argentite pyrite sphalerite galena tetrahedrite chalcopryite |
| North-eastern Humboldt Range (Arizona, Sheba, and DeSoto mines) | tuffaceous sandstone and conglomerate, also rhyolite | Triassic and possible late Paleozoic | late Cretaceous (?) | silicification, sericitization, pyritization | quartz, adularia calcite | pyrite arsenopyrite sphalerite galena freibergite jamesonite argentite native silver covellite |

TABLE 3 GEOLOGIC SUMMARY OF DISTRICTS (CONT.)

| District | Country Rock | Age of Country Rock | Age of Ore Deposit | Wall-rock Alteration | Characteristic Gangue | Minerals and Ore |
|-------------|-------------------|---------------------|--------------------|--|--|--|
| Reese River | quartz, monzonite | Jurassic (?) | Jurassic(?) | sericitization, some silicification and chloritization | quartz rhodochrosite calcite ankesite | pyrite galena sphalerite chalcopryrite arsenopyrite tetrahedrite enargite silver sulfantimonides sulfarsenides silver halides native silver |

Conclusions

The fact that supergene enrichment does occur at the Betty O'Neal mine is of less importance than the question of how it affected the tenor of the ore mined. Early reports confirm that supergene enriched ores of native silver and ruby silver (pyrargyrite) were the first deposits discovered. The ore mined in the early days, 1880's, was mainly from the Betty vein which must have had a relatively small zone of enrichment, because it had only a few years of minor recorded production.

Since the Estella vein provided the bulk of the ore mined in the 1920's and was the largest single producer in the entire district, most of the discussion will be limited to this vein. The case for valuable supergene enrichment is a dubious one. A question is immediately raised; are the specimens examined representative of the ore? Collecting specimens from the mine was difficult, because small veinlets and barren pillars were the only available sites for sampling. A few sample localities in the Estella vein and one specimen from the Mackay School of Mines museum had what appeared to be representative commercial ore. These ore samples all had a secondary mineral replacing galena and freibergite. After careful microscopic studies and a number of x-ray diffraction interpretations, this secondary mineral proved to be cerussite. Oxidation must have been pervasive to so frequently replace galena and the minerals intergrown with galena, usually freibergite.

The drill hole intersection of the vein with supergene wire silver and the presence of supergene pyrargyrite in the No. 1 Tunnel indicate that supergene processes were active at one time in the faulted extension of the Estella vein. The specimens examined from the main part of the

Estella vein show no supergene silver minerals while oxidation in the form of cerussite is abundant.

As was the case at the Sheba and De Soto mines in Pershing County, the Betty O'Neal was not minable at depth, but, in this exception to the general rule, the lack of good ore at depth does not indicate a significant enrichment zone. Excessively fractured rock below the main part of the Estella vein caused the diffusion of the vein into a group of stringers instead of a well-defined vein. N. H. Getchell (1927-1928), in his monthly reports to the owners of the Betty O'Neal mine, persistently maintained, that at depth the grade of ore in the mine remained the same as in the upper levels, but the veins narrowed and tonnage decreased.

The lack of outcrop of the Estella vein probably impeded enrichment from above by allowing insufficient movement of solutions to the vein. The former level of the water table in the mine may have been a major factor along with the lack of outcrop in the suppression of supergene enrichment. If the water table had been near to the present surface, as seems to have been the case considering the proximity of the supergene silver minerals to the surface, groundwater solutions with dissolved chemical weathering agents would have had a small zone to oxidize and leach. Thus, the source material for enrichment would have been lacking. Given time for erosion to remove enough surface rock and consequently lower the water table at the Betty O'Neal mine, the Estella vein would be exposed to the direct effects of oxidation and downward percolating surface water capable of extensive supergene enrichment.

The writer concludes that the known silver deposits at the Betty O'Neal mine, although containing a few supergene minerals, have had little

appreciable enrichment, and, conversely, may have been slightly impoverished by leaching due to widespread oxidation.

Secondary enrichment of silver in the Estrella extension may prove to be of great value to the ore when exploration reaches the vein near the drill hole intersection.

Bastin (1923, p. 93) gave some sage advice when he philosophized that "judgment as to the probable success of deep mining in veins rich in Ag near the surface should not be prejudiced by preconceived ideas of the importance of downward enrichment. Each district and, in some districts, each mine presents a special problem..."

Dodge, W. C., 1913, The Secondary Enrichment of Silver Ores: Jour. Geol., v. 21, p. 1-23.

Clark, E. F., and J. A. Carpenter, 1913, Nevada's Metal and Mineral Production, 1880-1910: Nevada Geol. Surv., v. 20, p. 75.

Edwards, A. S., 1954, Features of the Ore Districts: Melbourne, The Australian Institute of Mining, 242 p.

James, V. H., 1913, Enrichment of Sulfide Ores: U. S. Geol. Survey Bull., 570, 280 p.

———, 1917, The Enrichment of Ore Deposits: U. S. Geol. Survey Bull., 626, 510 p.

Ferguson, H. G., 1929, The Mining Districts of Nevada: Econ. Geol., v. 24, no. 2, p. 116-145.

Satwell, H. H., 1927-1928, General Manager's Monthly Reports for the Betty O'Neal Mine.

Wright, James, and Elcott Bates, 1955, Tectonic and Spinal Geology of the Northern Shoshone Range, Nevada: U. S. Geol. Survey Prof. Paper 488, 123 p.

Hill, J. A., 1925, Some Mining Districts in Northeastern California and Northeastern Nevada: U. S. Geol. Survey Bull., 594, p. 22-25, 75-114.

James, C. F., 1939, Geology of the Central Humboldt Range, Nevada: Univ. of Nevada Bull., 28, p. 72-73.

Bibliography

- Bastin, E. S., 1923, Discussion: Supergene Processes at Neihart, Montana: *Econ. Geol.*, v. 18, no. 1, p. 87-93.
- 1950, Interpretation of Ore Textures: *Geol. Soc. America Memoir* 45, 101 p.
- Burchard, H. C., 1882, Report of the Director of the Mint upon the Statistics of the Production of the Precious Metals in the United States, p. 138-139.
- Burgess, J. A., 1926, Report on the Geology of the Betty O'Neal Mine near Battle Mountain, Lander County, Nevada: unpublished report, 26 p.
- Cameron, E. N., 1939, Geology and Mineralization of the Northeastern Humboldt Range, Nevada: *Geol. Soc. America Bull.*, v. 502, p. 563-633.
- Cooke, H. C., 1913, The Secondary Enrichment of Silver Ores: *Jour. Geol.*, v. 21, p. 1-28.
- Couch, B. F., and J. A. Carpenter, 1943, Nevada's Metal and Mineral Production, 1859-1940: *Nevada Univ. Bull.*, v. 38, p. 74.
- Edwards, A. B., 1954, Textures of the Ore Minerals: Melbourne, The Australian Institute of Mining. 242 p.
- Emmons, W. H., 1913, Enrichment of Sulphide Ores: *U. S. Geol. Survey Bull.* 529, 260 p.
- 1917, The Enrichment of Ore Deposits: *U. S. Geol. Survey Bull.* 625, 530 p.
- Ferguson, H. G., 1929, The Mining Districts of Nevada: *Econ. Geol.*, v. 24, no. 2, p. 115-148.
- Getchell, N. H., 1927-1928, General Manager's Monthly Reports for the Betty O'Neal Mine.
- Gilluly, James, and Olcott Gates, 1965, Tectonic and Igneous Geology of the Northern Shoshone Range, Nevada: *U. S. Geol. Survey Prof. Paper* 465, 153 p.
- Hill, J. M., 1915, Some Mining Districts in Northeastern California and Northwestern Nevada: *U. S. Geol. Survey Bull.* 594, p. 22-29, 95-114.
- Jenney, C. P., 1935, Geology of the Central Humboldt Range, Nevada: *Univ. of Nevada Bull.* 24, p. 72-73.

- Ketner, Keith, 1965, Economic Geology, in Tectonic and Igneous Geology of the Northern Shoshone Range, Nevada: U. S. Geol. Survey Prof. Paper 465, p. 129-144.
- Knopf, Adolph, 1924, Geology and Ore Deposits of the Rochester District, Nevada: U. S. Geol. Survey Bull. 762, 78 p.
- Krauskopf, K. B., 1965, Geochemistry test, chapter 17, unpublished manuscript.
- Lindgren, Waldemar, 1933, Mineral Deposits: New York and London, McGraw-Hill Book Co., Inc., 4th ed., 930 p.
- Lovering, T. S., 1949, Rock Alteration as a Guide to Ore--East Tintic District, Utah: Econ. Geol. Monograph 1, 64 p.
- Palmer, W. S., 1924, Nevada's Newest Silver Producer--The Betty O'Neal Mine: Engr. and Min. Jour. Press, v. 117, no. 11, p. 449-452.
- Payne, A. L., 1967, Geological Report on the Betty O'Neal Silver Mine, Lewis Mining District, Lander County, Nevada: unpublished report, 68 p.
- Roberts, R. J., 1966, Metallogenic Provinces and Mineral Belts in Nevada: Nevada Bureau of Mines Report 13, Part A, p. 56, 61-63.
- Ross, C. P., 1953, The Geology and Ore Deposits of the Reese River District, Lander County, Nevada: U. S. Geol. Survey Bull. 997, 132 p.
- U. S. Bureau of Mines, Mineral Resources of the United States, 1882-1931, and Minerals Yearbook, 1932-1964.
- Vanderburg, W. O., 1939, Reconnaissance of Mining Districts in Lander County, Nevada: U. S. Bureau of Mines, I. C. 7043, p. 59-64.
- York, Bernard, 1944, The Geology of Nevada Ore Deposits: Univ. of Nevada Bull. 40, p. 1-76.