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THE MINERALOGY OF THE MOHAWK MINE SAN BERNARDINO COUNTY, CALIFORNIA

by

William S. Wise

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INTRODUCTION

Since the 1950's the Mohawk Mine has been known to mineral collectors as a source of interesting arsenates of zinc, copper, and lead, as well as zinc-manganese oxides and various carbonates. Over the past three decades the mine has been visited by numerous collectors, and through studies in several laboratories, a list of unusual or rare minerals and crystal habits has become known locally. However, no systematic description and interpretation of the minerals and ore deposit has yet been made. Through the enthusiastic support of several southern California mineral societies, this report was written to summarize the current state of knowledge concerning the geology and mineralogy of the Mohawk Mine. Specifically, this work will put the original ore body in the context of the tectonic framework of Clark Mountain and Ivanpah Mountain, summarize studies on all the minerals, and interpret the origin of secondary mineral assemblages.

Location and access to the Mohawk Mine

The Mohawk Mine consists of several adits on the south side (figure 1) and an incline and small adit on the north side of Mohawk Hill (secs. 7, 8, 17, and 18, T. 16 N. R. 13 E), which is between Clark Mountain on the north and the Mescal Range and Ivanpah Mountain to

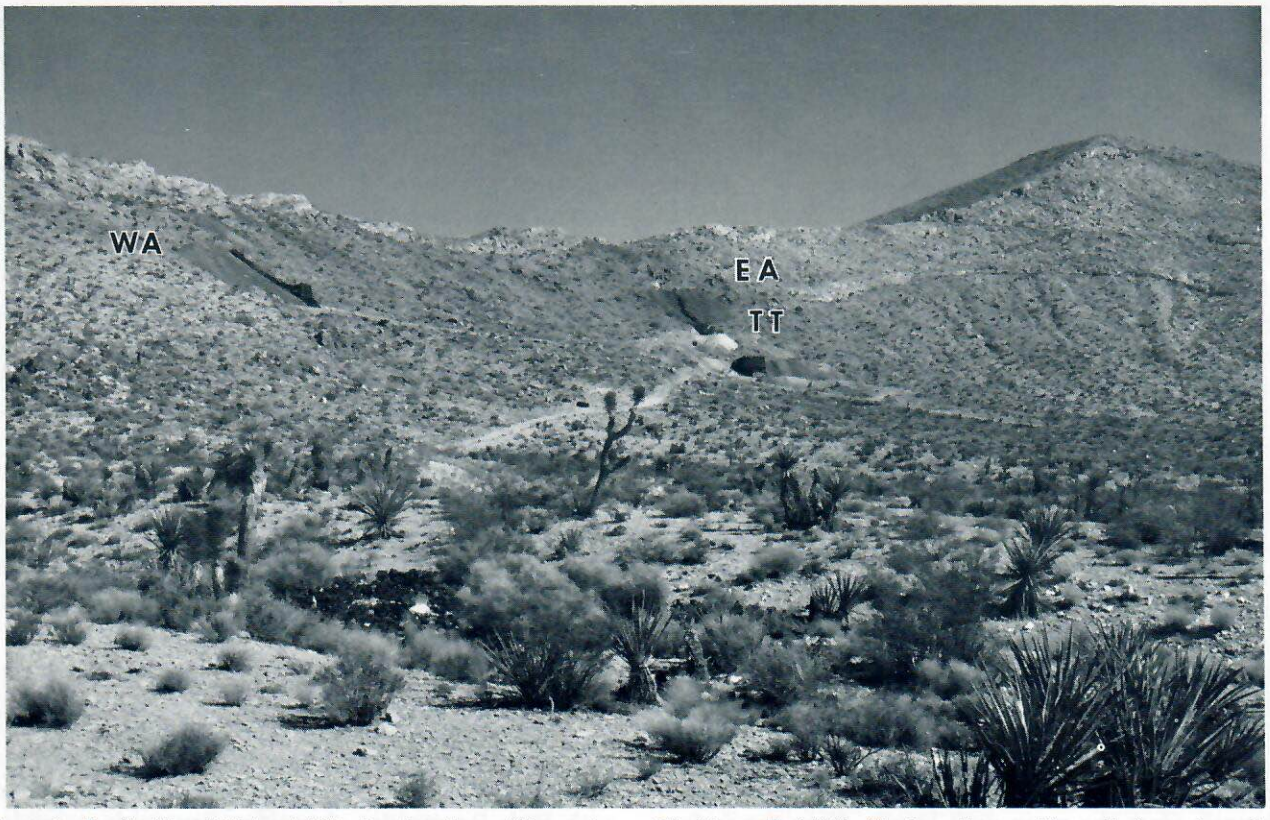

Figure 1. South side of Mohawk Hill, showing three of the major workings of the Mohawk Mine, WA - West Adit, TT - T Tunnel, and EA - Upper East Adit. The two other workings, that were important during the early mining activity, are on the north side of the ridge.

the south. These mountains, forming a major topographic high in eastern San Bernadino County, are transected by Interstate 15, the major highway connecting Los Angeles, California, with Las Vegas, Nevada. The mine is easily accessible from the Cima Road exit and a reasonably well maintained pipeline road that parallels I-15 toward the east (see figure 2). Following periods of dry weather this road is easily traveled by passenger vehicles, but should be approached with caution following rain storms.

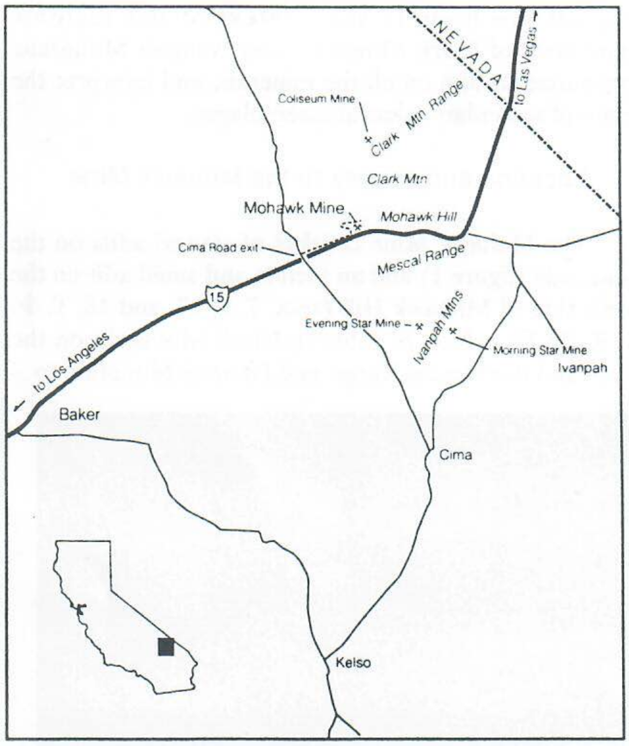

Figure 2. Map of northeastern San Bernardino County, California, showing the location of the Mohawk Mine.

The Mohawk Mine is inactive, but not an abandoned mine. Permission to collect must be obtained from the owner. As with any inactive mine, these workings should be entered with a great deal of caution. Typical hazards of old mines were well described by Voynick (1989), and several apply to the Mohawk Mine. For example, all the stopes have loose ceilings, and east side adits have inclines that drop abruptly from the main drift levels. Even the surface workings along the main ridge have unprotected shafts or stopes that drop vertically fifty to a hundred feet. Two of the adits (West Adit and Upper East Adit) are well ventilated by stopes that reach the surface, but the third, T Tunnel, has no circulating air. The dumps still contain representative samples from the ore zones of each of the major workings.

ACKNOWLEDGEMENTS

This report was prepared with the assistance of many people. Even though there is a risk of omitting someone, it is fitting to acknowledge their contributions here. All aspects of the preparation of this paper, including visiting the mine and mapping the underground workings, received enthusiastic support of Bill Hubbard, owner of the Mohawk Mine. The collection of Mohawk Mine minerals at the San Bernardino County Museum, curated by Bob Reynolds and arranged by Mac and Elyga Mansfield, was made available for laboratory study and photography. So were the private collections of Fred DeVito, Tibor Borhegyi, John Jenkins, Bob and Sugar White, Al Valenti, and Dave Yeomans. Ty Schuiling, Bob Reynolds, Ed Allabaugh, and Bob and Sugar White assisted in mapping the underground workings. Dave Pierce and Tracy Paul assisted in much of the microprobe analytical work and scanning electron microscopy. General contributions by participants of the biannual mineral workshops at the San Bernardino County Museum and the Pacific Micromount Symposium greatly broadened my understanding of the mineralogy of the mineral deposit at the Mohawk Mine.

Publication of the color plates was made possible through donations from the Southern California Micromineralogists, Inc., the Mineralogical Society of Southern California, the Southern California Chapter of the Friends of Mineralogy, the Mineral Research Society of California, and the San Bernardino County Museum Mineral Group; and from Jessie Hardman, Julia Curtis Baker, Elaine Sole, Lewis and Betty Carpenter, Bill and Mona Wise, Milton and Betty Speckels, Ken and Lois Boyson, Harold and Vi Fraser, Dr. Len Lobsenz, Don and Jean Hall, Mac and Elyga Mansfield, Bob and Juanita Curtis, and William Hubbard.

My views of the nature of the orebody, structure of the nearby geology, and various aspects of the mineralogy were greatly sharpened through discussions with Bob Reynolds. Jennifer Reynolds provided essential assistance in all aspects of the production of this paper.

MINING IN THE CLARK MOUNTAIN--IVANPAH MOUNTAIN AREA

The history, discovery, and exploitation of mineral deposits in the Ivanpah area in southern Nevada and eastern California have been reviewed by Hewett (1956, p. 144-115). Mining in this region began in 1854 with the discovery of the lead-zinc deposit at Potosi in the Goodsprings district. By 1864, several silver and gold occurrences in the Ivanpah and Clark Mountains had been found, but until 1892, when the Santa Fe railroad was completed, the region was too remote for extensive mining. Even then the low prices for base metals kept mining activity at a minimal level until 1905, when the Union Pacific Railroad track between Barstow and Salt Lake City (and passing through Ivanpah, figure 2) was completed. This stimulated a renewed period of prospecting and mining, which continued through the time of the first World War.

The Mohawk Mine was apparently discovered sometime in the early 1900s, because by 1916 L. O. Godshall had established the mine, patented six claims, and developed a mill site. Production during the first World War was reported as 2,893 tons assaying at 2.1% copper, 15.5% lead, 2.8% zinc, and 9.6 ounces of silver (Wiebelt, 1949). According to Hewett (1956), who did most of his field work on the Ivanpah quadrangle in the 1920s, most of the early mining was from an inclined shaft on the north side of Mohawk Hill. Only minor exploration work was done on the south side of the ridge. With the reduced demand for base metals following the war, the mine shut down.

The mine remained idle until 1942 when Dunton, Ray, and Greenwood arranged lease agreements with the owner, Ivanpah Copper Co., L. O. Godshall, vice president and manager. F. J. Wiebelt of the U. S. Bureau of Mines visited the mine in 1945 to conduct a drilling program, and gives the following description of the development of the ore bodies.

> Mining was begun originally on the outcrop from pits and a shallow shaft [near the top of the ridge above the eastern orebody]. Later the east tunnel was driven to intersect the eastern ore body at an elevation 50 feet below the bottom of the shaft [this is the Upper East Adit of figure 1]. The western ore body was developed by the west tunnel, which was driven on the limestone-monzonite contact (Wiebelt, 1949, p. 3).

Operations in the 1940s

> ...started from these two tunnels, which served until the 'T' tunnel was driven at an elevation 240 feet below the outcrop. Ore was intersected at a point about 200 feet from the portal, and a great part of [the] production was obtained from development and stoping from this level. In addition to the stoped area there are about 2,000 feet of drifts, crosscuts, and winzes in the east and west ore bodies" (Wiebelt, 1949, p. 3).

Mining between 1942 and 1952 produced 16,723 tons of ore with a metal content of 206 ounces of gold, 92,802 ounces of silver, 183,600 pounds of copper, 3,065,500 pounds of lead, and 1,094,800 pounds of zinc (Hewett, 1956, p. 146).

There are a number of small gold, silver, and base metals deposits in the Clark Mountain and Mescal Range area in similar geologic settings to that of Mohawk Mine (Hewett, 1956, pl. 2). Current mining activity is confined to gold ore bodies at the Morning Star and Coliseum (or Colosseum) mines (figure 2). The Mountain Pass Mine, which recovers rare earth elements from bastnaesite in Precambrian carbonatite dikes, is a much older and different kind of mineralization than that under discussion here.

GEOLOGIC SETTING

The Clark Mountains, Mescal Range, and Ivanpah Mountains encompass a fold and thrust belt that was mapped by Hewett (1956) in reconnaissance during the 1920's. He recognized that upper Precambrian and lower Cambrian sediments of the Grand Canyon series had been pushed from west to east into overturned folds and thrust faults. More recent mapping has shown that these ranges are actually built of stacks of thrust plates. To the south and west these structures have been intruded by the Teutonia Batholith, a group of intrusions with ages that span the Cretaceous Period (136-92 Ma, Beckerman et al, 1982). The compression and magmatic activity were parts of regional mountain-forming events that affected the whole Cordillera. During the Tertiary Period the same region began extending, forming the Basin and Range Province. This extension was accommodated by normal faulting, some on very low angle planes, and was accompanied by scattered volcanic activity.

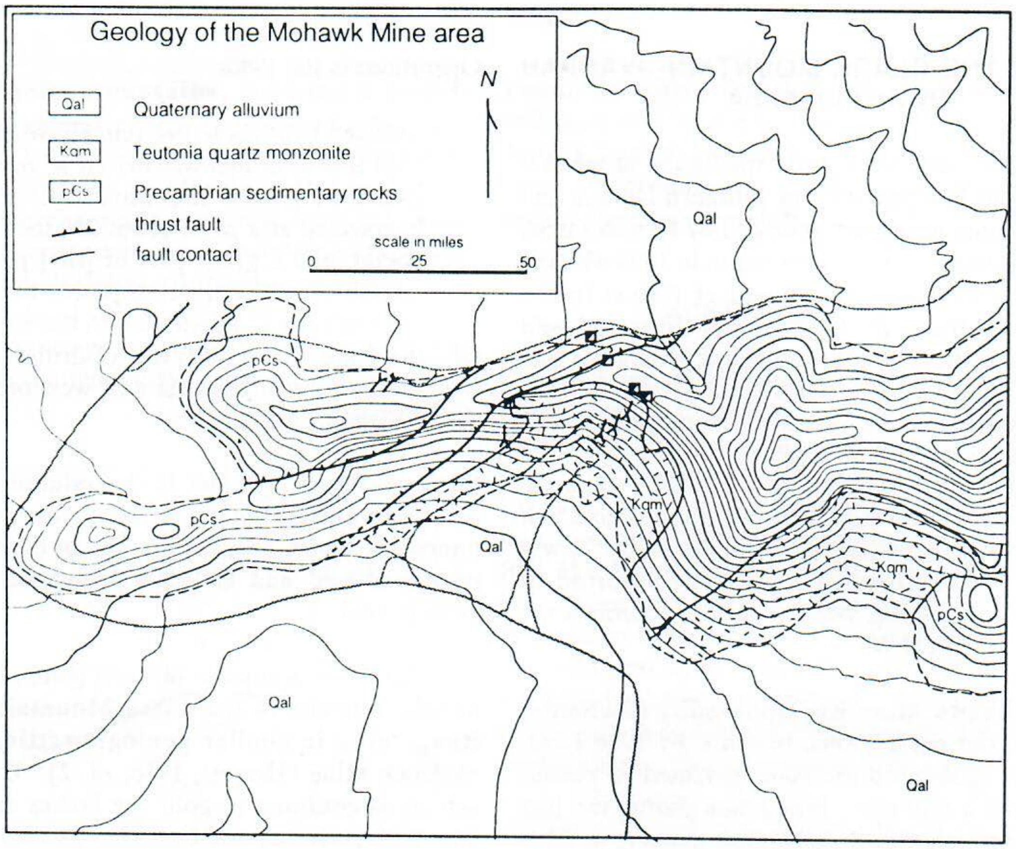

Figure 3. Geologic map of the Mohawk Mine area. Base topography and roads are from the Mescal Range Quadrangle, U.S.G.S. 7½ minute series.

On the west end of Mohawk Hill, the folded and thrust-faulted sedimentary rocks are mostly dolomites and limestones of the late Precambrian Noonday Formation. The reversed sequence includes an exposure of quartzite on the far west end. Of particular importance to the ore deposits, however, is the occurrence of fault bounded blocks of Teutonia quartz monzonite. Most previous mapping has considered these to be intrusive, and therefore younger than the folding and thrust faulting. However, several aspects of the contact suggest that the quartz monzonite and carbonate sedimentary rocks are bounded by faults. Most importantly, the carbonate rocks show no effects of thermal metamorphism, but are instead brecciated and recrystallized. Furthermore, the quartz monzonite is extensively shattered and sheared throughout its areal extent. These field relations suggest the quartz monzonite may have been transported by Mesozoic faulting, or it may have been emplaced by normal faulting in the late Tertiary.

Even with the recognition that the quartz monzonite is bounded by faults, the relationships are complex (see figure 3). From west to east the fault between carbonate rocks and the quartz monzonite strikes NE and dips SE. The fault then curves into an E-W strike along the ridge and has a southerly dip. Above the Upper East Adit the fault strikes NW and dips SW. In all three areas the quartz monzonite forms a concave hanging wall.

The character of the deformation of the quartz monzonite places some constraints on the faulting history of the Mohawk Mine area. Throughout the mine area, the quartz monzonite has been subjected to two periods of deformation. The first formed a set of fractures along which some ductile shearing took place, and during which much of the plagioclase was altered to sericite. The shear zones are up to 1 mm wide, and are filled with recrystallized quartz and sericite. Quartz crystals are strained with minor cracking and rehealing. Because of the extensive conversion of plagioclase to sericite and the complete lack of epidote, this deformation must have been accompanied by K^+ metasomatism.

The second deformation produced shears cutting the first set at angles between 60° and 80°. These highly pervasive shears are spaced 3 to 10 mm apart, which means that nearly every crystal in the rock has been broken. Quartz is extensively sheared, but recrystallized. Sericite from the first deformation is sheared and recrystallized. Biotite, the only mafic mineral in the quartz monzonite, has been replaced by muscovite and magnetite.

The differences in alteration products, spacing between the shears, and extent of recrystallization indicate that the two sets of shears represent two separate times of deformation. These are most likely related to episodes of faulting. The replacement of plagioclase by sericite and the recrystallization of quartz requires temperatures above about 300°C (Rose and Burt, 1979). This indicates that the initial phase of deformation and severe shearing of the quartz monzonite must have occurred at some depth.

The ore veins were emplaced along the faults and breccia zones related to the faults, primarily between the carbonate sedimentary rocks and the quartz monzonite. It is important to note that the breccia along the thrusts in the carbonate sequence has been mineralized. However, the greatest volume of mineralization occurs within the carbonate breccia developed below the hanging wall of the spoon-shaped quartz monzonite blocks. None of the veins appears to have been deformed or faulted, which suggests that ore deposition occurred after or during the latest faulting. From the examination of the geologic relationships in the close vicinity of the Mohawk Mine, there does not seem to be clear evidence to indicate the timing of various faulting events and the emplacement of the ore bodies.

MINERALOGY

Introduction

The ore removed by the mining operation consisted of massive limonite[1/] with scattered concentrations of secondary minerals of lead, zinc, copper, and silver. Remnants of this ore remain scattered along many of the workings of the mine and on the dumps of the three principal adits. It is these secondary minerals that have been of interest to collectors and mineralogists over the past several decades and will be the focus of this report. Table 1 is a list of these minerals and their relative abundance.

When sufficient specimen material was available, the identification of each of the species in Table 1 was verified by data obtained from petrographic microscopic examination, x-ray powder diffraction patterns, or electron microprobe analyses. X-ray powder diffraction methods were commonly sufficient to verify initial guesses based on crystal habit, color, and association. Several minerals, however, exhibit such a wide range of habits or so closely resemble other species that complete chemical analyses were required. These analyses were obtained with an ARL EMX electron microprobe equipped with a Tracor energy dispersive analyzer, which allows data collection using both the wave length and energy dispersive systems. Standards for quantitative analysis include willemite (Zn), hematite (Fe), anglesite (Pb, S), mimetite (Pb, As), cuprite (Cu), K-feldspar (K, Al, Si), and rhodonite (Mn). Peak overlaps were resolved by stripping techniques (Super ML, as supplied by Tracor), and interelement effects were corrected by a ZAF program, as supplied by Tracor and modified at UC Santa Barbara.

Distribution of secondary minerals

Even though many of the secondary minerals were probably distributed throughout the ore zones of each of the three major adits, the present distribution in the exposures left by the underground workings is uneven. Significant occurrences of the major minerals are illustrated on the maps of the three major adits, shown in figures 4, 5, and 6. Reference is made to these figures to illustrate occurrences in the descriptions of the individual minerals.

Descriptions of secondary minerals

Adamite, $Zn_2(AsO_4)(OH)$. Adamite is one of the more common arsenate minerals in the Mohawk Mine. Single crystals are elongated parallel to the b-axis and have the typical sphenoid terminations (figures 7 and 8). They range in size up to 2 mm, and commonly form radiating clusters. Some adamite is nearly colorless to pale sherry, but most is pale green, bluish green, or green (see Plate 1). The green color is a result of varying amounts of copper in the zinc positions of the crystal structure. Although the pure copper end member,

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[1/] *Throughout this report the term limonite is used to refer to rock masses consisting predominantly of goethite, but commonly associated with other minerals such as hematite, pyrolusite, and quartz.*

Table 1.
List of minerals from the Mohawk Mine
San Bernardino County, California

Primary minerals

ankerite
chalcopyrite
galena
gold
quartz
sphalerite
rhodochrosite*
arsenopyrite*

* *These minerals were not found in remnants of the primary veins, but their existence is inferred from the secondary minerals.*

Secondary minerals

	crystallinity	occurrence
adamite	XX	common
agardite	xx	rare
anglesite	m	rare
aragonite	XX	common
arseniosiderite	xx	rare
aurichalcite	XX	common
austinite	xx	common
azurite	XX,xx	common
beudantite	xx	common
brochantite	XX	rare
calcite	XX	common
carminite	xx	rare
cerussite	XX	rare
chalcanthite	XX	v.rare
chalcophanite	XX	common
chlorargyrite	XX	rare
chrysocolla	m	common
conichalcite	xx,m	rare
copper	m	v.rare
cuprite	m,ps	rare
delafossite	m	rare
dioptase	xx	v.rare
duftite	xx	common
epsomite	xx	v.rare
fluorite	XX	rare
fraipontite	xx,m	rare
goethite	m	v.common
hemimorphite	XX	common
hetaerolite	XX	rare
hidalgoite	xx	rare
hydrohetaerolite	xx	rare
jarosite	XX	rare
malachite	XX	common
mimetite	XX	common
olivenite	xx	rare
pyrolusite	XX	rare
rosasite	XX	common
quartz	XX	common
sauconite	m	common
scorodite	XX,ps	rare
smithsonite	XX	common
sulfur	xx	v.rare
tsumcorite	xx	rare

Crystallinity: XX - crystals or groups easily discernable with standard microscopes; xx - crystalline, but individual crystals too small to see easily; m - occurs as masses with crystals much too small to see except with the scanning electron microscope; and ps - form occurs but has been pseudomorphed (replaced) by a later mineral.

Occurrence: Common - mineral is easily found in workings or on dumps; rare - mineral can be found, but only in a few specific localities; v.rare - only a few specimens have been found.

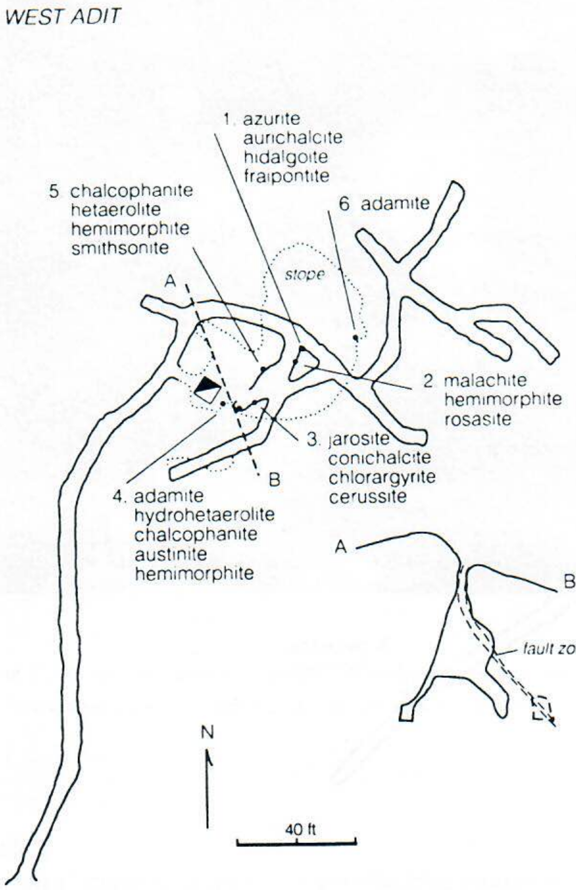

Figure 4. Map of the West Adit with locations of notable secondary minerals that have been collected over the past decade. Adit was mapped by W. Wise and R. White 1989.

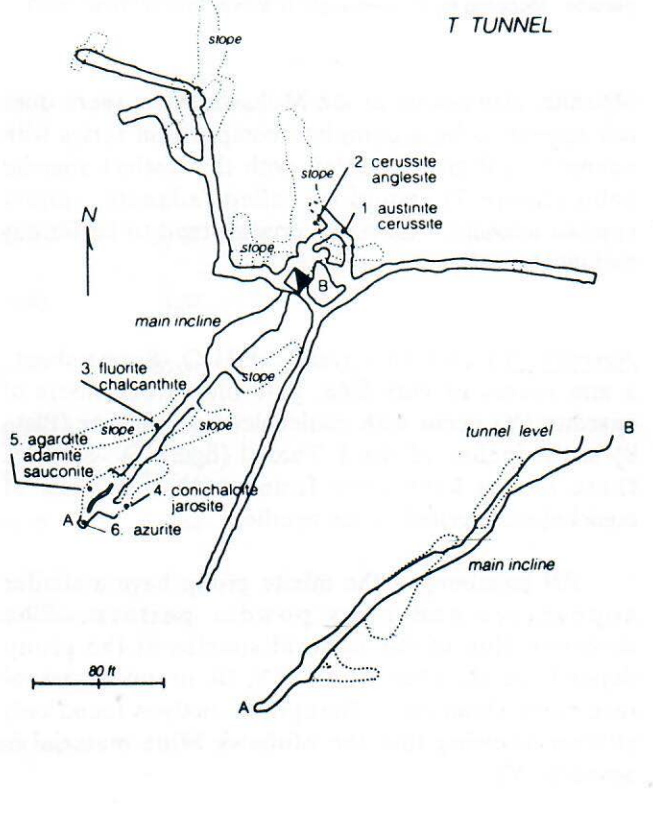

Figure 5. Map of the T Tunnel with locations of notable secondary minerals that have been collected over the past decade. Mapping by R. Reynolds and W. Schuiling, 1989.

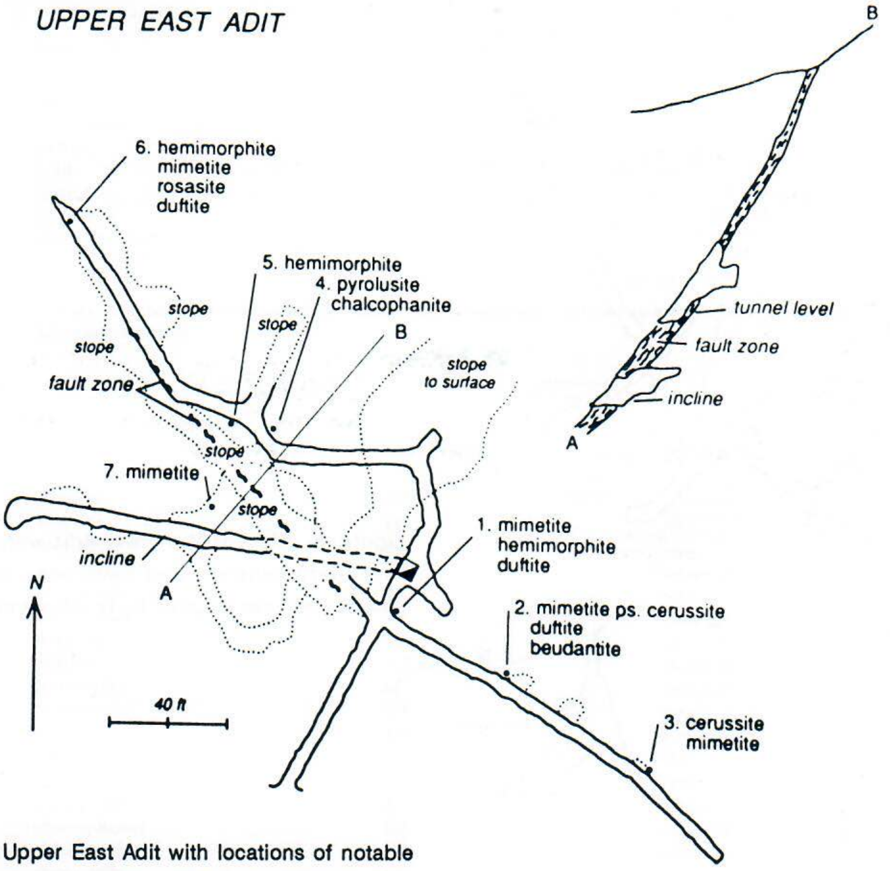

Figure 6. Map of the Upper East Adit with locations of notable secondary minerals that have been collected over the past decade. Mapping by E. Allabaugh, S. White, and W. Wise, 1989.

olivenite, also occurs at the Mohawk Mine, there does not appear to be a complete composition series with adamite. All green crystals with the distinct adamite habit (figure 7) should be called "adamite, variety cuprian adamite." Olivenite crystals tend to be fibrous and much smaller.

Agardite-(Y) $(Y,Ca)Cu_6(AsO_4)_3{}^{a}3H_2O$. Sprays about 1 mm across of very fine, pale blue-green fibers of agardite-(Y) occur with conichalcite and quartz (Plate 3) in the incline of the T Tunnel (figure 5). Some of these sprays have been found with tiny balls of conichalcite perched on the needles.

All members of the mixite group have a similar appearance and x-ray powder pattern. The determination of the mineral species of the group depends on the abundance of Y, Bi, or any of several rare earth elements. Microprobe analysis found only yttrium, showing that the Mohawk Mine material is agardite-(Y).

Anglesite, $PbSO_4$. Anglesite most commonly occurs as masses surrounding the remnants of galena crystals. This material has an adamantine luster and ranges from dark gray to colorless. If cavities exist in these specimens, anglesite and cerussite can commonly be found projecting into them.

Aragonite, $CaCO_3$. Aragonite occurs scattered through the workings as thin, colorless needles. One spectacular occurrence is in the far end of the drift of the Upper East Adit. Here, water flowing from the surface along a crack between the granitic rock and dolomite has deposited calcite and aragonite over the hanging wall surface. Aragonite needles have grown like spikes on the surface of amorphous-appearing balls of carbonate.

Arseniosiderite, $Ca_3Fe^{3+4}(AsO_4)_4(OH)_6{}^{a}3H_2O$. Arseniosiderite commonly occurs as thin cavity coatings or, rarely, as small mounds of lustrous tan to reddish

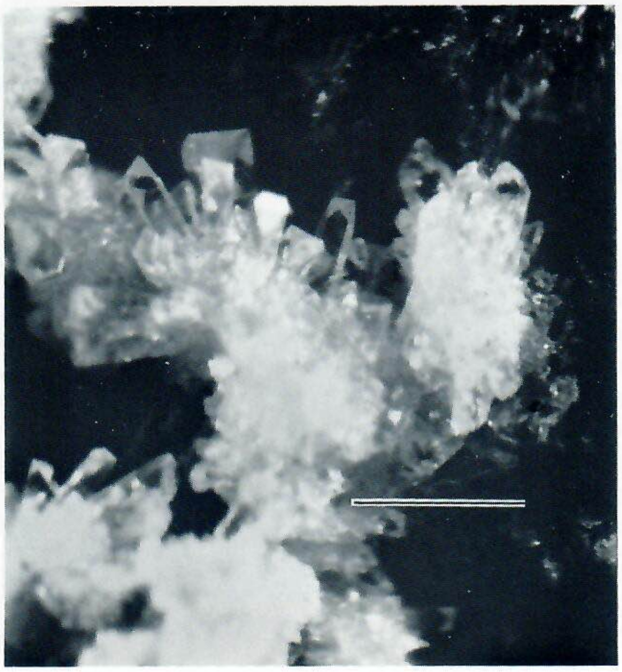

Figure 7. Colorless adamite crystals, showing the typical prism form elongated parallel to the b axis. Length of bar is 0.5 mm.

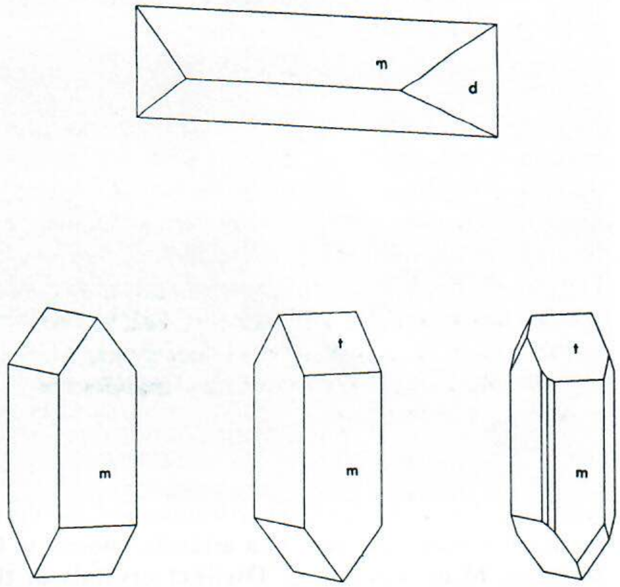

Figure 8. Crystal forms of adamite and austinite. a) Adamite forms, d - {101), m - {110}, typical at the Mohawk Mine. Many of the cuprian variety have very short d faces, giving an octahedron-appearing crystal. b and c) Simple crystal forms of left handed and right handed austinite, where m - {110} and p - {111}. d) More complex habit of austinite.

Table 2.
Chemical analyses of austinite-conichalcite minerals, Mohawk Mine.

	1	2	3	4	5
CaO	20.91	20.50	20.32	20.50	20.94
CuO	26.65	19.8	15.85	3.45	1.37
ZnO	4.35	11.99	16.78	28.47	30.31
As_2O_5	40.30	41.76	41.26	43.34	43.79
total	92.23	94.08	94.23	95.78	96.44

Samples and copper content

1. Conichalcite, 87 mole percent copper.
2. Conichalcite, 63 mole percent copper.
3. Cuprian austinite, 49 mole percent copper.
4. Austinite, 11 mole percent copper.
5. Austinite, 4 mole percent copper.

brown, tiny plates. These cavity coatings are commonly covered with beudantite and mimetite. Where uncovered the mineral is difficult to recognize as being different from the limonitic host rock.

Aurichalcite, $(Zn,Cu)_5(CO_3)_2(OH)_6$. A typical carbonate mineral from copper and zinc deposits, aurichalcite is most prevalent in the West Adit working, especially locality 1. Crystals are commonly long, pale blue blades that fill cavities in the limonitic gossan (see Plate 1). In the West Adit, blades of aurichalcite, which reach 1 cm in length, are limited only by the size of cavities. Common associated minerals are hemimorphite (Plate 3) and rosasite. Its color and habit make it easy to recognize.

Austinite, $CaZn(AsO_4)(OH)$. Austinite and its cuprian variety is a relatively common arsenate mineral in the Mohawk Mine workings. Distinct crystals of this mineral are rare, although some excellent specimens up to 1 mm in length have been collected (Plate 1). These are prismatic elongated parallel to the c-axis and are distinctly enantiomorphic, i.e. there are left and right handed crystals. Many of the crystals are simple combinations of the forms $\{110\}$ and $\{111\}$ in right handed crystals and $\{110\}$ and $\{1\bar{1}1\}$ in left handed crystals (see figure 8). As in other localities the number of right and left handed crystals are approximately equal. A few crystals have a more complex combination of forms (figure 8). The majority of the austinite from the Mohawk Mine is greenish and occurs as balls formed of radiating prisms about 0.5 mm in length. The copper analog of austinite, conichalcite, also occurs at the Mohawk Mine, and there appears to be a complete compositional series between these minerals (Table 2). There is no reliable way to distinguish between cuprian austinite and conichalcite, other than with a microprobe analysis.

An interesting variety of austinite was found on the dump of the Upper East Adit (figure 9). X-ray powder diffraction studies showed these white platy crystals to be similar to austinite, and microprobe analysis revealed significant amounts of lead substituting for Ca in the austinite (similar to the relationship between conichalcite and duftite).

Azurite, $Cu_3(CO_3)_2(OH)_2$. Azurite is relatively common throughout the mine workings, and is easily recognized by its deep blue color. Other minerals with this color do not occur at the Mohawk Mine. Some of the best examples of this mineral (Plate 2) were found at locality 1 in the West Adit (figure 4), where it forms single bladed crystals up to 2 mm long. At this locality it is partially replaced by fraipontite or, less frequently, malachite.

Beudantite, $PbFe^{+3}_3(AsO_4)(SO_4)(OH)_6$. For several reasons beudantite has been especially difficult to recognize in specimens from the Mohawk Mine. It occurs in a variety of habits, ranging from single, pseudocubic crystals (Plate 1) to hexagonal plates in rosettes, to wafers in irregular clusters, and massive crusts. Beudantite is a member of a large group of minerals, all with similar crystal forms and x-ray powder patterns. Furthermore, there are compositional gradations between individual species, requiring microprobe analyses to be certain of the mineral identity.

Beudantite commonly forms coatings on cavities in limonitic boxwork. These coatings are brown to yellow-brown and highly lustrous. Crystals are generally poorly defined, but where they can be discerned, pseudocubic or platy forms predominate. The larger crystals (1 mm across) are dark brown; with smaller size, the color grades into yellow-brown and yellow. There are many specimens of single crystals or crystal clusters scattered on limonitic surfaces. Such material has been ideally suitable for study of crystal habit and composition.

Figures 10 and 11 illustrate the common habits of beudantite at the Mohawk Mine. The symmetry of the jarosite-beudantite group of minerals is rhombohedral with axial ratios ($a:c = 2.3251$) such that the common rhombohedron form, $\{01\bar{1}2\}$, closely resembles a cube. The angle between edges of these pseudocubic crystals is 92°, very close to the 90° of a true cube. Very commonly these rhombohedrons have a truncated corner (figure 12) that is an important clue that the crystal is indeed not a cube.

Another common form is the flat, hexagonal-appearing plates (figures 10 and 11), formed of the basal pinacoid, modified by two rhombohedrons. The tiny balls and other rosettes of beudantite consist of clusters of flat plates (figure 10). The common, indistinct form of beudantite is dominantly plates, but with a stepped surface on the c-pinacoid, giving the crystal a disc shape (figure 10). The steps are probably formed by alternating pinacoid and rhombohedron development. A few specimens of scalenohedral crystals have been

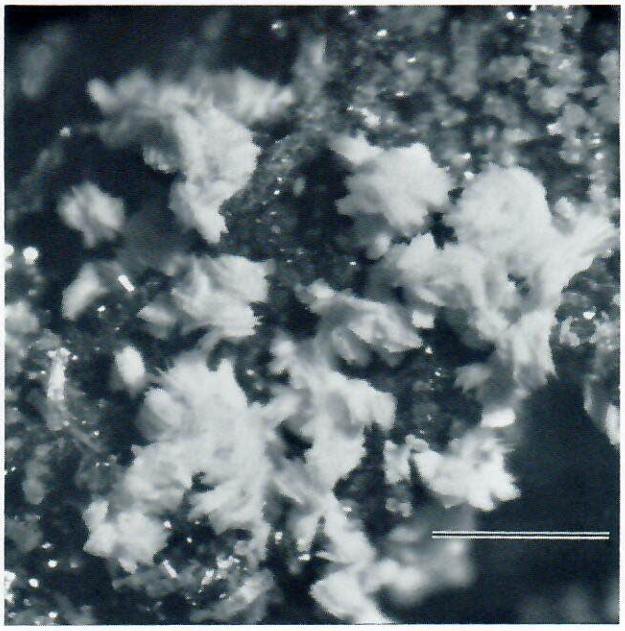

Figure 9. Austinite, variety plumbian austinite, with small prisms of mimetite from the dump below the Upper East Adit. Note that this variety of austinite crystallizes in plates or laths rather than the prismatic form shown in figure 8. Length of bar is 0.5 mm.

Figure 10a

Figure 10b

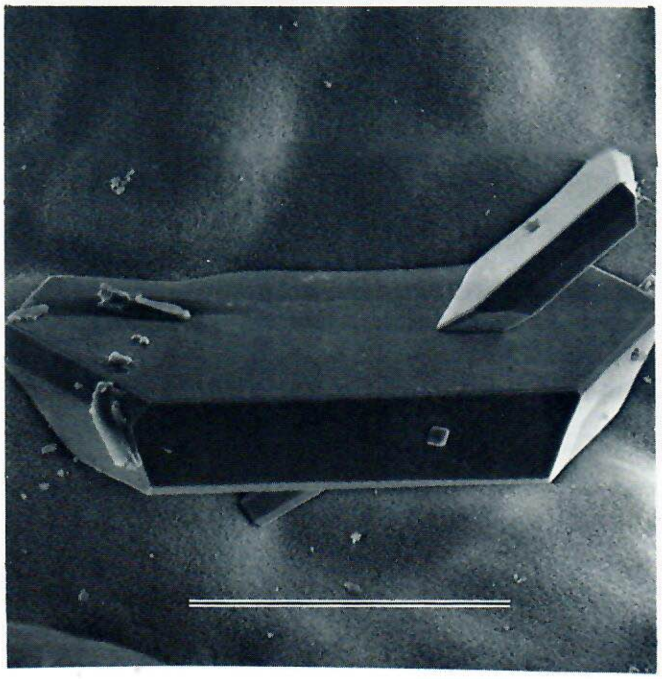

Figure 10. Scanning electron photomicrographs of four different habits of beudantite. a). Pseudocubic habit with small c-pinacoid (see figure 12). Length of bar is 0.1 mm. b) Tabular habit with large c-pinacoid (see figure 12). Length of bar is 0.1 mm. c). Rosette of plates. Length of bar is 0.01 mm. d) Lense-shaped crystals with stepped surface caused by alternating rhombohedron and c-pinacoid faces. Length of bar is 0.1 mm.

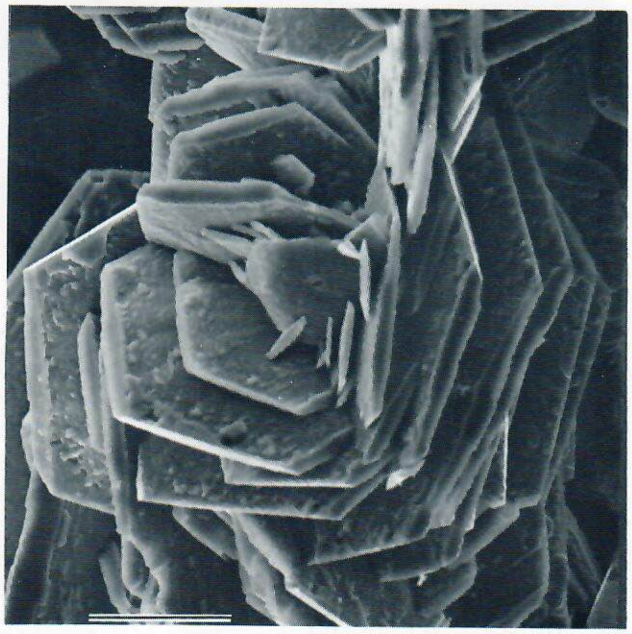

Figure 10c

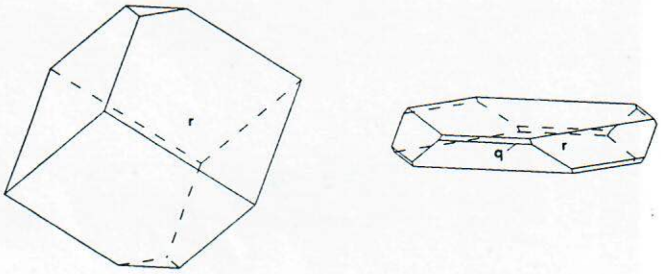

Figure 11. Crystal forms of beudantite. a) Pseudocubic form, b) and platy form with r - {$10\bar{1}2$}, q - {$10\bar{1}1$}, and c - {0001}.

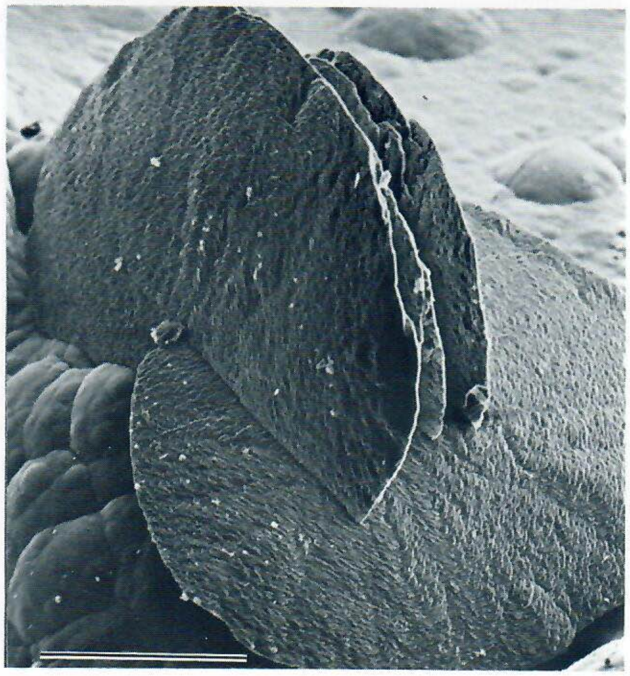

Figure 10d

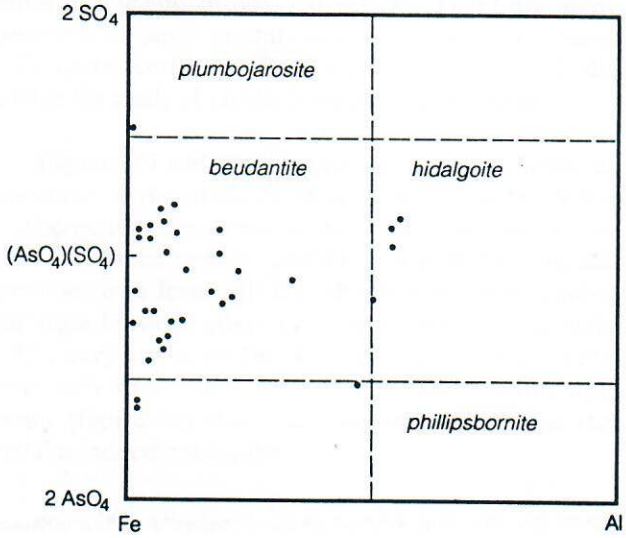

Figure 12. Plot of beudantite and hidalgoite compositions, to show the variation in As/S and Fe/Al contents. Note that the great majority of points fall within the beudantite field. The four within the hidalgoite field are all green crusts and represent samples from the West Adit. For all others there is no systematic correlation between composition and crystal habit nor with the locality from which the sample came.

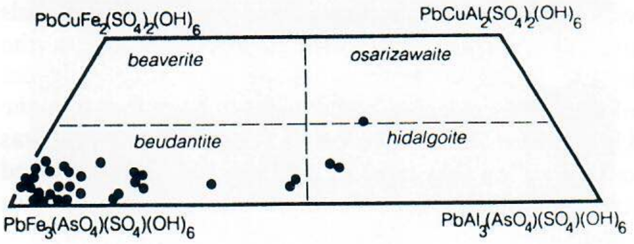

Figure 13. Plot of beudantite and hidalgoite compositions, to show the extent of copper plus zinc substitution. The greenest of the hidalgoite samples are on the border with osarizawaite.

found, in which the crystal form may be {0111}. A few specimens of yellow-brown prismatic crystals that were shown to be beudantite by x-ray diffraction are possibly pseudomorphs after mimetite. The prism form on beudantite is unknown.

A selection of beudantite with a variety of forms and from a variety of associations were analyzed with the microprobe. All compositions obtained are plotted in figures 12 and 13, and selected analyses are given in Table 3. The variations revealed by these data illustrate different kinds of isomorphous substitution. The ideal composition of beudantite has one AsO_4 and one SO_4, but it is clear from figure 12 that few of the crystals have this exact content. Replacement of the arsenate ion by sulfate causes the composition to trend toward plumbojarosite, and replacement of sulfate by arsenate causes a trend toward the composition of "sulfate-free beudantite", as yet unknown as a mineral. Independently, the ferric iron ion may be replaced by Al, trending toward the composition of hidalgoite. There appears to be little corrleation between crystal form and composition. The pseudocube form was not compositionally distinct from that of the platy forms. However, some of the disc-shaped beudantite have the lowest sulfate content.

Beudantite is commonly associated with mimetite, carminite (Plates 1 and 2), and duftite. Jarosite has the same crystal form and color as the platy form of beudantite. The only way to distinguish between these two species is based on the association of beudantite with mimetite.

<u>Brochantite</u>, $Cu_4(SO_4)(OH)_6$. A few specimens containing this emerald green mineral were found on the dump below the Upper East Adit. The brochantite is associated with delafossite, malachite, and cuprite. Its blocky, prismatic habit and slow solution in dilute acids distinguishes it from the similar-appearing malachite. The restricted occurrence of this mineral may be related to the lack of abundant chalcopyrite or other copper sulfides in the primary ore.

Table 3.
Chemical analyses of
beudantite and hidalgoite, Mohawk Mine
and beudantite, Tsumeb Mine, Namibia

	1	2	3	4
PbO	30.76	31.97	34.34	31.77
ZnO	1.14	0.0	0.66	0.23
CuO	0.0	0.23	2.48	0.06
Al_2O_3	1.77	1.19	12.15	1.06
Fe_2O_3	30.37	33.02	15.73	33.04
SO_3	10.72	8.04	12.92	11.06
As_2O_5	14.92	18.21	14.79	13.90
total	89.68	92.70	93.07	91.15

Samples and structural formulas:

1. Beudantite, pseudocubic form, Mohawk Mine.

$Pb_{0.97}[Fe_{2.69}Al_{0.25}Zn_{0.1}Cu_{0.02}]\,(AsO_4)_{1.07}(SO_4)_{0.95}(OH)_6$

2. Beudantite, lensoidal form, Mohawk Mine.

$Pb_{1.05}[Fe_{3.03}Al_{0.17}Zn_{0.0}Cu_{0.02}]\,(AsO_4)_{1.16}(SO_4)_{0.73}(OH)_6$

3. Hidalgoite, Mohawk Mine.

$Pb_{1.03}[Fe_{1.32}Al_{1.60}Zn_{0.0}Cu_{0.21}]\,(AsO_4)_{0.86}(SO_4)_{1.08}(OH)_6$

4. Beudantite, Tsumeb, Namibia

$Pb_{1.03}[Fe_{3.00}Al_{0.15}Zn_{.02}Cu_{0.0}]\,(AsO_4)_{0.87}(SO_4)_{1.00}(OH)_6$

Figure 14. Platy habit of calcite; width of crystal is 4mm. J. Jenkins photo.

Calcite, $CaCO_3$. Calcite occurs throughout the mine workings as small, colorless rhombohedral and scalenohedral crystals. It appears very similar to smithsonite, and requires a test with acid to be certain of its identity. Some calcite occurs as flat, disk-shaped crystals (figure 14), a form very uncommon in smithsonite. Most, if not all, of the calcite in the workings was derived by surface water carrying the calcium and carbonate ions from the dolomite and limestone outcrops to depth. Therefore, calcite is common in fractures and less common in gossan cavities.

Carminite, $PbFe^{+32}(AsO_4)_2(OH)_2$. The tiny, bright red crystals that are associated with beudantite and mimetite are carminite. Although it is relatively common, distinct crystals are rarely seen. The shape and relative size of carminite crystals can be seen in the scanning electron photomicrograph of figure 15, where it has overgrown beudantite. Several examples of carminite having replaced mimetite are also known (Plate 2).

Cerussite, $PbCO_3$. Distinct crystals of the simple carbonate of lead are surprisingly rare in the mine workings. Some of the best examples are associated with anglesite surrounding galena "eyes". The crystals are colorless, prismatic with striations parallel to the length, and highly lustrous. Some interesting examples of mimetite replacing cerussite have been found in the Upper East Adit. The original cerussite crystal was coated with a thin layer of goethite and then dissolved away; mimetite sprays form in the resulting cavities (Plate 4).

Chalcanthite, $CuSO_4{}^a5H_2O$. Curving, pale blue crystals of chalcanthite were found near the base of the incline in the T Tunnel (figure 5). This mineral is characteristic of areas of active oxidation of copper sulfide minerals, and is therefore not found in other parts of the mine, because so very little of the original sulfide minerals remain.

Chalcophanite, $(Zn,Fe^{+2},Mn^{+2})Mn^{+43}O_7{}^a3H_2O$. Chalcophanite, one of three Zn-Mn oxide minerals found at the Mohawk Mine, occurs most commonly in the form of plates, jumbled together in crusts about 1 mm thick, or in ball-like clusters up to 2 mm across (figure 16). In the thicker plates, shown in figure 16c,

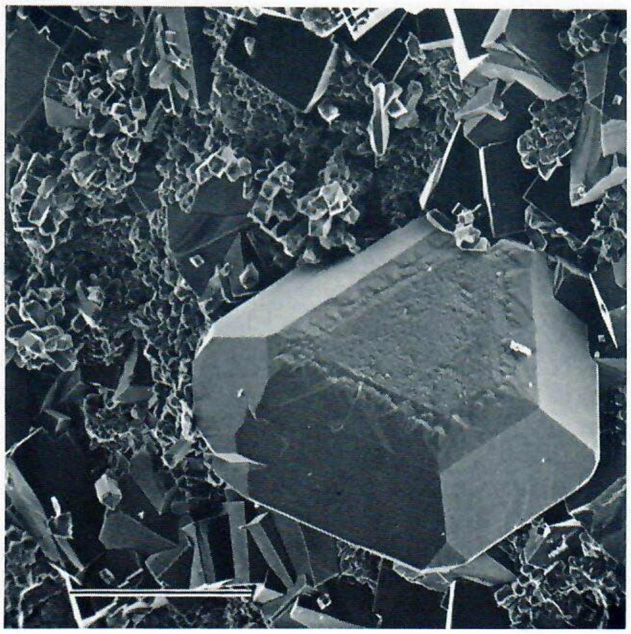

Figure 15. Scanning electron photomicrograph of carminite (c), beudantite (b), and a large mimetite crystal. The length of the bar is 0.1 mm.

Figure 24a

Figure 24b

Figure 24. Two habits of smithsonite. a) Typical steep scalenohedrons, and b) an unusual combination of scalenohedron and pinacoid forms. J. Jenkins photos.

NATURE AND ORIGIN OF THE ORE BODIES AT THE MOHAWK MINE

There were several ore bodies in Mohawk Hill, all emplaced along faults or fracture systems in the dolomites of the Noonday Formation. The size and orientation of these ore bodies can be determined from the mine workings. The best example and most easily appreciated, even by the casual observer, is in the Upper East Adit. The drift toward the east (to localities 1, 2, and 3 in figure 6) follows a vein 2 to 6 feet wide and sloping toward the south. The other ore bodies are also vein systems, which vary in thickness and direction. The west and north side of Mohawk Hill has scattered small veins that were explored, but ore was too minor for exploitation. Emplacement of ore was along fractures and breccia planes. The most important breccia reservoir was the one developed below the curving, relatively impervious, non-reactive quartz monzonite hanging wall.

The minerals in all of the ore bodies are oxidation products of earlier sulfide minerals. There is only scant evidence to indicate the nature of the primary minerals of the veins. One specimen of unoxidized vein material contained galena (PbS), sphalerite (ZnS), chalcopyrite ($CuFeS_2$) and minor gold in a gangue of ankerite ($CaFe(CO_3)_2$) and quartz. These sulfide minerals account for many of the secondary minerals, except that the great abundance of goethite and hematite must have come from pyrite. Furthermore, the secondary arsenate minerals, such as mimetite, must have come from the oxidation of an arsenic sulfide, such as arsenopyrite (FeAsS) or enargite (Cu_3AsS_4). The occurrence of scorodite with jarosite is strongly suggestive of an arsenopyrite precursor. Oxidation of enargite tends to produce an abundance of copper arsenate minerals, which are very rare or absent at the Mohawk Mine.

The sporadic occurrences of hetaerolite and chalcophanite indicate that the original veins must have included a source for the manganese. A common gangue mineral in veins of this sort is rhodochrosite ($MnCO_3$), which was mentioned in early reports of the mineralogy of the Mohawk Mine (Hewett, 1956), but has not been observed in the collections studied here.

Most of the veins were formed at the contacts between the quartz monzonite and dolomites of the Noonday Formation. As described earlier, all these contacts are faults. Where the fault and veins cut through only dolomite, the wall rocks were enriched in iron, possibly converting some of the dolomite to ankerite. These veins are easily found on the surface, because weathered ankeritic dolomite stains the outcrop brown.

Veins containing galena, sphalerite, and chalcopyrite are common in epithermal systems, near-surface veins formed by deposition from hot water. The complete lack of thermal metamorphism of the carbonate rocks indicates temperatures did not exceed 250° to 300°C. There is not an obvious source for the fluids that deposited the vein minerals in Mohawk Hill, nor is there clear evidence as to when the deposition occurred.

It is interesting to note that the Mohawk Mine, the Evening Star Mine, and the Morning Star gold mine (figure 2) have several similarities, especially the geologic setting and mineralogy. At the Morning Star Mine, pyrite, chalcopyrite, galena, sphalerite, covellite, and silver-gold occur in calcite and quartz veins. The veins are located along faults and fractures in the hanging wall block above the Morning Star Thrust Fault. The Ivanpah Granite phase of the Teutonia Batholith forms both the foot and hanging walls of the fault; no carbonate rocks were involved in the mineralization. At the Evening Star mine, lead, zinc, and copper minerals were deposited in the carbonate wall rocks associated with skarn developed along the margin of the Teutonia quartz monzonite.

ORIGIN OF SECONDARY MINERALS

Oxidation of the primary sulfide ore minerals

All sulfide minerals are unstable in the presence of oxygenated water, that is, water in contact with air, such as rain or vadose water. Uplift of the Clark Mountain-Ivanpah Mountain block and subsequent erosion gradually brought the sulfide veins of the Mohawk ore body above the water table and into contact with freshly oxygenated water. Exposure of the sulfide minerals to this water caused them to oxidize. The initial reaction varies with the specific sulfide mineral, but the overall effect is for metals to go into solution and reprecipitate as carbonate, sulfate, arsenate or oxide minerals in cavities and fractures.

Certainly one of the first minerals to react to the new oxygen-rich environment was pyrite. The sulfide form of sulfur oxidizes readily to sulfate, which causes the surrounding water to become strongly acidic. As long as the water has a pH less than about 2, iron from the pyrite will remain in solution, but if the solution is diluted somewhat by fresh surface waters, the iron will precipitate as goethite or hematite. The initial dissolution of the iron and somewhat later precipitation allows its transport into the surrounding rock, forming the familiar gossan. As the sulfide minerals dissolve through oxidation boxwork cavities are left behind (figure 26). Sphalerite and chalcopyrite react with oxygenated water in much the same fashion as pyrite, but the zinc and copper precipitate only at much higher pH's. The solution carrying these metals commonly comes in contact with water from the surface saturated in carbonate ions (from atmospheric CO_2), which cause the formation of smithsonite and malachite or azurite.

The oxidation of the sulfur in galena immediately precipitates the lead as anglesite regardless of the pH, but may later react with carbonate-carrying water to form the lead carbonate, cerussite. Anglesite commonly forms an impermeable jacket around some of the galena, preventing further oxidation, which is why such galena "eyes" can still be found in the oxidized ore zones. Rarely the oxidation of the sulfur may stop midway, allowing the formation of elemental sulfur. The silver in the Mohawk Mine ores almost certainly was a minor constituent of the galena, and was released into solution by the oxidation.

The oxidation of arsenopyrite results in an interesting variation on the general theme. Both the iron and arsenic oxidize and, if the pH is very low, will

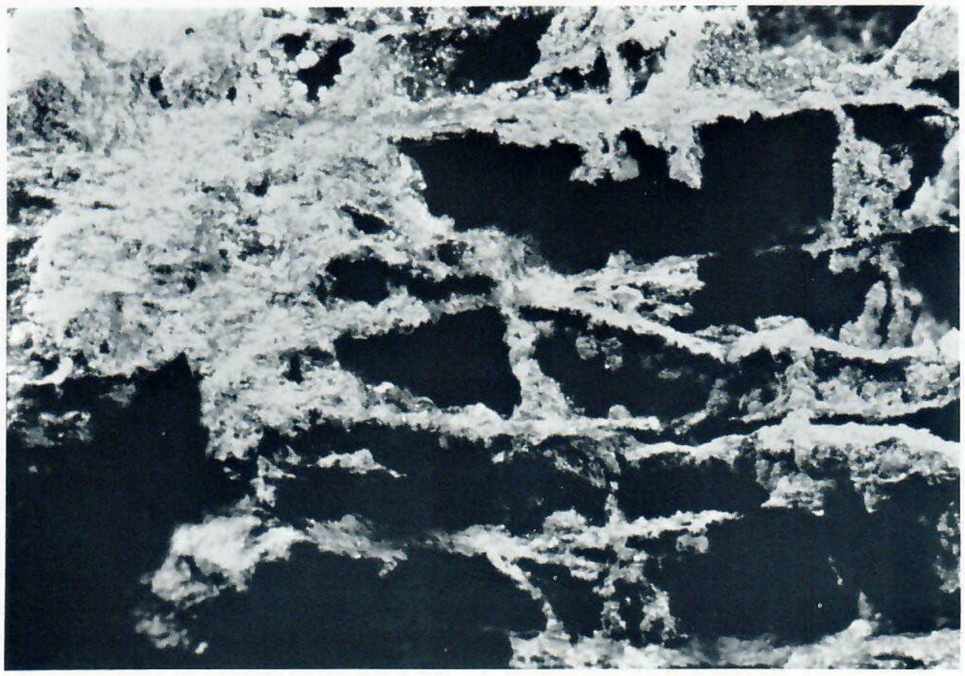

Figure 26. Typical boxwork structure. Walls are composed of limonite that was precipitated along cleavage planes of a sulfide mineral as it was beginning to oxidize. In this case the sulfide mineral was sphalerite. After the remaining sphalerite was dissolved away, small smithsonite crystals grew in the resulting cavities. Width of the field of view is 6 mm.

precipitate as scorodite. If the pH of pore solutions subsequently rises, the scorodite will redissolve, leaving behind either hematite or limonite, and the common ferric iron sulfate, jarosite. However, the arsenate ion also forms many other insoluble compounds with iron in combination with other metals, or with other metals alone under less acid conditions. Such minerals are beudantite, carminite, tsumcorite, duftite, adamite, mimetite, austinite, and conichalcite.

Controls on the origin of secondary minerals

Many investigators of secondary base metal deposits have attempted to develop a scheme to explain the observed sequences of mineral growth. One of the more successful of these was that developed for the secondary minerals at the Tsumeb Mine, Namibia, by Keller (1977). He sorted through a great number of observed reactions, inferred from sequences of minerals, and displayed the results on a time vs pH diagram (Keller, 1977, p. 46). At Tsumeb the reactions involve such a large number of different metal ions and anions that the diagram can only be a broad summary. However, Keller's diagram illustrates an interesting trend, in which the earliest minerals formed under acidic conditions and were gradually replaced as the waters became increasingly less acidic with time.

At the Mohawk Mine, the mineral sequences vary from locality to locality. In some, the earliest minerals must have formed under strongly acid conditions, e.g. scorodite. In others the early minerals were carbonates, smithsonite or cerussite, stable only in neutral or basic water. The difference between the two types is easily explained by the access of circulating surface water to the oxidizing sulfide minerals. In the first, water circulation was so restricted that acid produced by oxidation could not be diluted. In the second, surface waters were available to dilute and neutralize the metal-bearing acidic water.

Most of the early formed carbonates have been replaced by later arsenate and/or sulfate minerals, because the continuing oxidation produced these cations along with more acid water. The general pattern of these sequences is illustrated on a Keller-type diagram in figure 27. This diagram places minerals along general

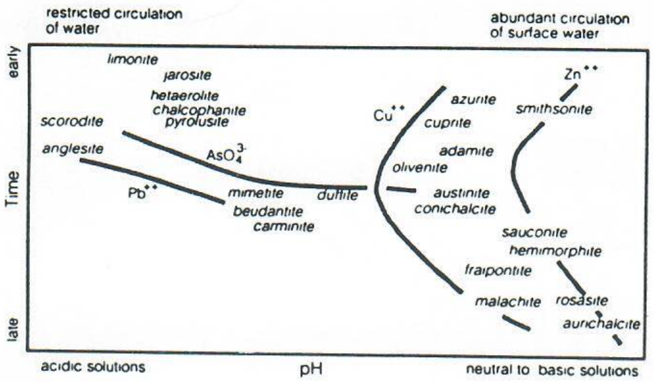

Figure 27. Sequences of crystallization of the more important secondary minerals at the Mohawk Mine.

paths where cations and anions must reach saturation. It does not show the effects of one cation on the stability of other minerals.

Placing such quantitative limits on the stability of specific minerals requires accurate solubility data, which has been available for some of the more common minerals, but has only recently become available for many arsenates. An instructive example is the effect of copper ion activity (concentration) and pH on mimetite stability. The recent work of Inegbenebor et al (1989) has shown that mimetite is stable in relatively acidic water (figure 28). Increasing copper ion activity will tend to favor the lead-copper arsenate minerals, bayldonite and duftite, and the copper arsenates. These minerals can replace mimetite at moderate pH's and copper contents. The lack of bayldonite at Mohawk indicates copper ion activities were seldom high in the presence of both lead and arsenate ions.

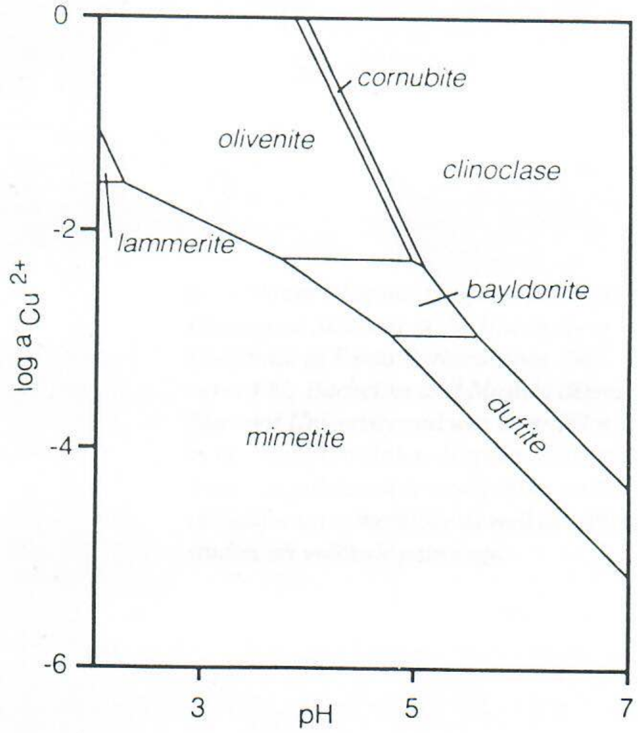

Figure 28. Activity (concentration) of copper ions - pH diagram, showing the stability field of mimetite as it is bounded by copper arsenates. The diagram (after Inegbenebor et al, 1989) is drawn with $a_{Pb} = 10^{-7}$ and $a_{Cl} = 10^{-3}$ mol/l.

Even though the number of different assemblages of secondary minerals (that is, stable groups of minerals) is fairly limited, the variety is controlled by many local factors, such as permeability (ready access of surface waters) and abundance of specific kinds of primary sulfide minerals. Much of the enjoyment of collecting and studying secondary base metal minerals comes from trying to decipher these factors for specific specimens, especially for ones with pseudomorphs. The Mohawk Mine has consistently yielded specimens that are fine examples of particular mineral species, but are intriguing puzzles from a paragenesis point of view.