PETROLOGY OF THE ALGOMAH MINE AREA ONTONAGON COUNTY, MICHIGAN

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ABSTRACT

PETROLOGY OF THE ALGOMAH MINE AREA
ONTONAGON COUNTY, MICHIGAN

By Chester H. Wilson

The Algomah mine area is located in Ontonagon County, Michigan. The Keweenaw fault, which traverses the area, has placed the Portage Lake lava series in contact with the Jacobsville sandstone.

Copper mineralization of the Algomah flow top consists of copper chlorides, carbonates, silicates, and oxides instead of the usual native copper of the Lake Superior region.

All outcrops in this area were sampled and thin sections prepared. Polished sections were prepared of ore samples. These sections were studied using standard microscopic techniques.

The results showed that the flow tops had been albitized during the mineralization. A possible mechanism involving Precambrian salt deposits for the deposition of hypogene native copper would account for the sodium enrichment of the flow top and provide the chloride involved in the supergene mineralization.

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By

Chester H. Wilson

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INTRODUCTION

Much copper has been mined from the Precambrian Portage Lake lava series of the western Upper Peninsula of Michigan. Most of this copper has been found as native metal. The Algomah mine differs from most of these mines in that it carries a copper ore, black cupric oxide, instead of the usual native copper. Various phases of the unique mineralogy of this area have been previously examined and it is the purpose of this thesis to correlate the results of this work with a petrological study of the area.

GEOGRAPHY

The Algomah mine area is located 1½ miles east of Mass, Michigan in section 3, T 50 N, R 38 W (Figure 1). This area is easily reached by highway M 35 and county roads. The area is covered fairly extensively by glacial deposits, with rock outcropping only in the immediate vicinity of the mine. Most of the area is swampy and of little economic use except for dairy farming and pulpwood production.

History of Algomah Mine

The Algomah mine was originally worked with poor results by a company of the same name from 1852 to 1854. On June 4, 1910 the Algomah Mining Company was organized and exploratory work commenced. During 1910 an assay of

Figure 1

Location of Area

a sample from sixty tons of selected ore contained 24% copper. Exploration continued into 1911 with underground development from the shaft and with diamond drilling. In 1912 S. R. Dow, the company president, went bankrupt, losing $ 28,725 which should have been in the company treasury. As a result the company reorganized and called for a $1 per share assessment to provide $70,000 to continue development. Shaft sinking continued and in 1914 74,560 pounds of hand picked ore from the developmental work yielded 12,467 pounds of copper, a yield of 18%.

The mine was idle from 1914 to April 1915 when work started again after a sale of delinquent stock bid in by the company for non-payment of the 1912 assessment. After hand picked ore stoped from the first level proved unprofitable, the company devoted itself to sinking the shaft hoping to strike the rich Lake Lode to the north. By the end of 1915 the shaft was down to 478 feet. 5,005 pounds of copper were sold at 18¢ per pound from the hand picked ore.

In 1916 the shaft was sunk 80 feet to a depth of 558 feet. However, in 1916 and 1917 the company was plagued by high costs and adverse labor problems and closed with a total of $16,868.54 in the treasury.

In 1955 the mine was opened for the third time,along with some others in the area, and operated for thirteen months. At this time selected ore stoped from the first

level gave 16% to 20% copper but the necessity of shipping it to the Atlantic Coast made the venture unprofitable.

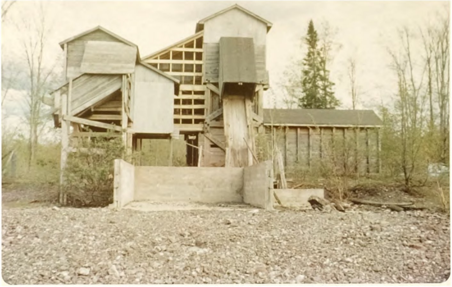

Photo 1. Algomah Copper Mine

Previous Investigations

The Algomah mine and the mines nearby, the Lake and South Lake, have proved interesting to many people because of the rather unique mineralization and structure of the area, although little is published on the region. Lane (1909) incorporates the general results of the exploratory work in the area in his Keweenaw Series of Michigan but is inclined to simplify the regional structure by attributing all structural features to faulting as he states:

"--- I may have been too much influenced in my feeling that there is no such fold, by the fact that no similar folds have heretofore been notices." (1)

Other than company reports, early information of the area is mostly confined to Michigan Geological and Biological Survey mineral production reports which give general geological and production facts. R. E. Hore in his article "The Copper Industry of Michigan" in the 1910 report states:

"The Algomah lode is the upper portion of a brown amygdaloidal bed and differs markedly from all of the lodes (studied) in carrying black oxide, green silicate and green carbonate of copper instead of native metal. Along the strike it shows masses of green colored ore more or less separated by stretches of brown amygdaloid." (2)

The unique mineralogy at Algomah is indicated as he continues:

"The copper minerals in the Algomah lode are chiefly chrysocolla, melaconite and malachite. The oxide is usually dull black massive melaconite; but Prof. A. E. Seamen has found specimens showing black tetragonal crystals of paramelaconite in green malachite. This is the only known occurrence of paramelaconite other than that at the Copper Queen Mine, Arizona, where it was first identified by Dr. Koenig. Prof. Seamen has also found in the Algomah ore some minute green crystals which are thought to be dioptase." (2)

Stevens (1911) and Hore (1912, 1914) repeat essentially

1) Lane, Alfred C., The Keweenaw Series of Michigan, Publication 6, Series 4, Volume 2, Michigan Geological and Biological Survey, Lansing, Michigan, 1909, page 947.

2) Hore, R. E., "The Copper Industry of Michigan", Mineral Resources of Michigan, 1910, Publication 8, Geological Series 6, Michigan Geological and Biological Survey, Lansing, Michigan, 1912, pages 34-35.

the same information as in Hore's 1912 report. However, it is apparent that the structure of the area was unclear as shown by this statement from Hore's 1912 article:

"President R. M. Edwards reports of the results of explorations: 'A Study of the drill cores has yet given no satisfactory explanation of the conflicting results obtained. Apparently on the northwestern part of the property adjoining the Lake and South Lake in the vicinity to drill holes Nos. 5, 6, and 7, there are copper deposits at considerable depth, but which way they dip and where they come to the surface is undetermined.'" (3)

Evidently the structure was becoming clearer in 1914 when Hore stated:

"The (Algomah) lode strikes nearly north and dips to the west at an angle of about 70° at the shaft." (4)

Hopper in 1915 stated that:

"It is believed by General Manager Edwards that at depth some of the lodes worked in the Lake and South Lake will be encountered on the Algomah property." (5)

Hopper (1914, 1915,1916) reports the economic situation of the company which, as indicated before, was very unstable.

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3) Hore, R. E., "Michigan Copper Industry in 1912", Mineral Resources of Michigan, 1912, Publication 13, Geological Series 10, Michigan Geological and Biological Survey, Lansing, Michigan, 1913, pages 19-20.

4) Hore, R. E., "Michigan Copper Deposits", Mineral Resources of Michigan, 1914, Publication 19, Series 16, Michigan Geological and Biological Survey, Lansing, Michigan, 1915, page 70.

5) Hopper, W. E., "The Michigan Copper Industry in 1915", Mineral Resources of Michigan, 1915, Publication 21, Geological Series 17, Michigan Geological and Biological Survey, Lansing, Michigan, 1916, page 19.

Butler and Burbank in The Copper Deposits of Michigan mention the area in a number of places. Mention is made of the unique mineralogy previously studied along with the note that:

"Atacamite ($Cu_2Cl(OH)_3$) occurs in well-formed radiating crystals as an oxidation product at the Algomah mine." (6)

The structure of the area is summarized by them:

" At the Lake and South Lake mines there is a broad, gentle syncline (Lake mine syncline or Lake mine basin) and a narrow, steep anticline between the (Keweenaw) fault and the point where the rocks have the normal westerly dip." (7) "The shaft on the Algomah lode is on the south side of the Lake mine basin, at the general horizon of the Lake lode and only 60 feet from the Keweenaw fault. Whether or not this lode is the same as the Lake lode has not yet been determined." (8)

From their study they also determined that:

"--- the lode is mainly cellular---" (8)

and that:

"The rock showed pumpellyite rock alteration characteristic of many of the lodes in this part of the district." (8)

Zinn (9) mapped this area in 1942 for the Michigan Geological Survey and this report is listed in An Index of Michigan Geology as an open file report. However, it

6) Butler, B. S., and Burbank, W. S., The Copper Deposits of Michigan, United States Geological Survey Professional Paper 144, United States Geological Survey, Washington, D. C., 1929, page 58.

7) Butler and Burbank, ibid, pages 48-50.

8) Butler and Burbank, ibid, page 217.

9) Zinn, Dr. Justin, personal communication, 1966.

cannot be located by the Michigan Geological Survey and seems to have been missing for a number of years.

Spiroff (1942) includes a few outcrops in the Algomah area on his map of the Firesteel River area.

Williams (1962a, b) made an excellent study of the ore minerals found at Algomah using samples from the A. E. Seamen Museum at Michigan Technological University, Houghton, Michigan. He found the paragenesis of the copper minerals to be as follows:

"--- (oldest to youngest) native copper - cuprite - dioptase - paramelaconite - plancheite - atacamite - paratacamite - nantokite - tenorite - malachite - chrysocolla." (10)

10) Williams, S. A., "Stability Relations and Paragenesis of Copper Oxides and Chlorides at the Algomah Mine, Ontonagon County, Michigan", Economic Geology, Volume 57, 1962a, page 111.

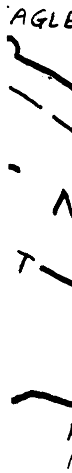
GENERAL GEOLOGY

Lithologic Setting

The formations of the Keweenaw peninsula are, from the oldest to youngest, the Portage Lake lava series, Copper Harbor conglomerate, Nonesuch shale, Freda sandstone, and Jacobsville sandstone. The Portage Lake lava series is locally intruded by a small rhyolite body. A generalized map of Keweenawan geology is included here as Figure 2.

The Portage Lake lava series is a thick sequence of flows ranging in composition from olivine basalt to andesite with a few interbedded conglomerates with rhyolitic pebbles. These flows vary in thickness from a few hundred feet up to about 1300 feet and in extent along the strike from a few hundred feet up to at least 40 miles. Some of the flows are uniformly fine-grained but most of them increase in grain size from both the top and bottom towards the center. The texture of the coarse-grained lavas may be ophitic, glomeroporphyritic, or less commonly, porphyritic.

Capping the massive lava that forms the bulk of each flow is a large layer of amygdaloidal lava usually 5 to 10 feet thick. A few flows have, in addition, small to large amounts of detrital sand, silt, or clay in cracks and interstices between fragments in those



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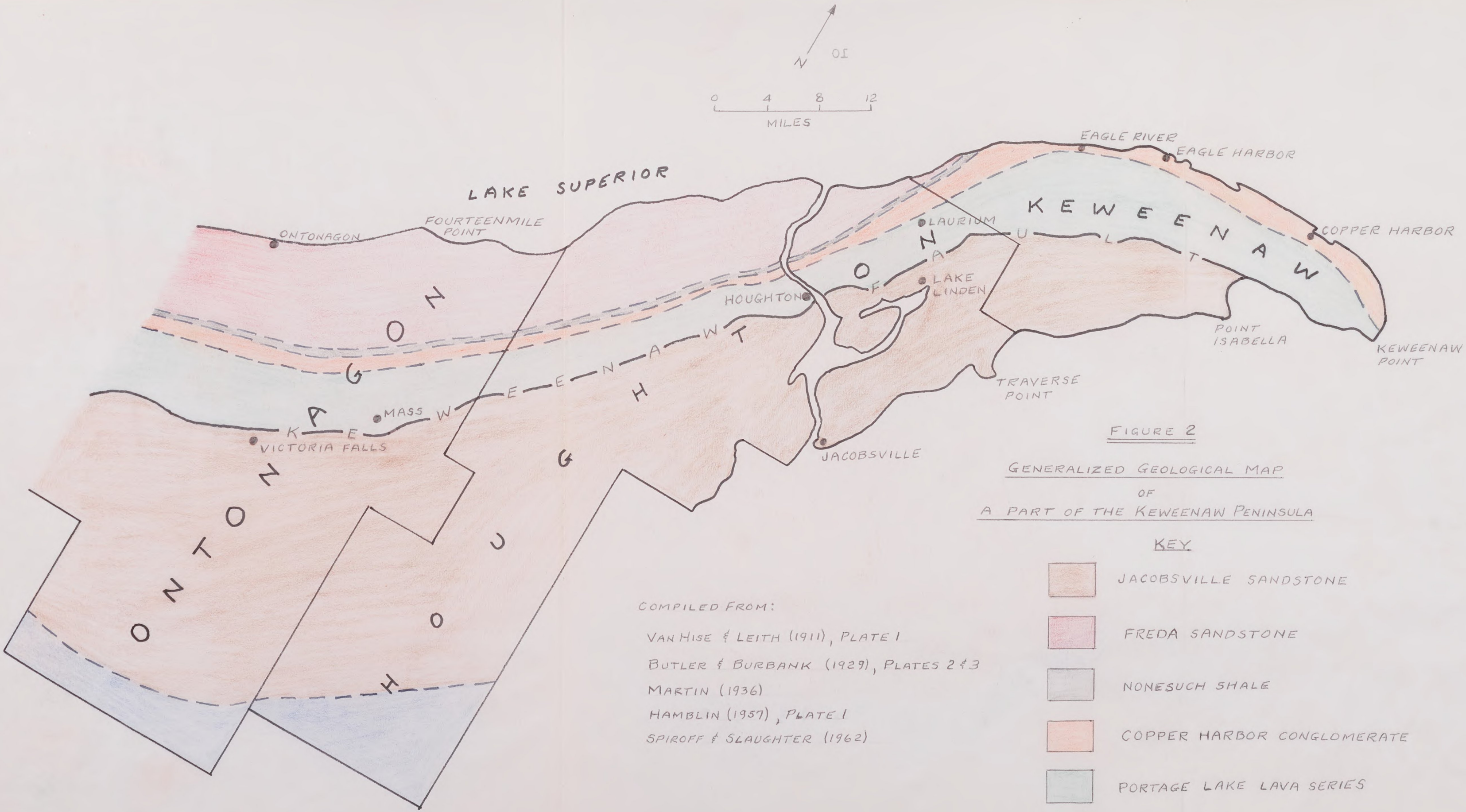


FIGURE 2

GENERALIZED GEOLOGICAL MAP OF A PART OF THE KEWEENAW PENINSULA

flows with fragmental tops. The minerals filling the amygdules are mainly calcite, epidote, and quartz, although other minerals such as prehnite, datolite, red potash feldspar, analcite, native copper, pumpellyite, and laumontite are locally abundant.

The conglomerate and sandstone beds within the lava series are composed primarily of rhyolitic material. The bulk of the clastic particles range in diameter from a small fraction of an inch to about 6 inches. The pebbles and cobbles are generally well rounded. These rocks are compact and tightly cemented. These sedimentary beds serve as good stratigraphic markers and a few have native copper deposited in them.

The Copper Harbor conglomerate that conformably overlies the Portage Lake lava series consists mainly of rudely stratified pebble-to boulder-conglomerate with small sandstone lenses and beds. The pebbles and boulders are well-rounded to sub-angular rhyolite clasts. Basalt fragments are generally present in small amounts and in some areas make up as much as one-half the total bulk. There is little pre-Keweenawan material present. The matrix is sand and grit of the same character as the coarser material.

Lava flows interstratified with the Copper Harbor conglomerate are typically fine-grained andesite, with an amygdaloidal layer 2 to 10 feet thick at the top. The dominant minerals of the amygdaloidal fillings are calcite, chlorite, and laumontite.

The Nonesuch shale is predominantly siltstone. The upper part of the formation is composed of flaggy, ripplemarked, gray to reddish-gray siltstone, with small amounts of interbedded gray and greenish-gray silty shale. The lower part contains dark gray siltstone, mostly thinly laminated, with several beds of coarse-grained arkosic sandstone near the base. The lower part contains chalcocite and native copper in the White Pine area near Ontonagon. The total thickness of the formation is about 600 feet.

The typical rock of the overlying Freda sandstone is a light gray to red, fine to medium-grained sandstone with prominent white blotches and streaks. The formation includes minor amounts of red shale and conglomerate. The total thickness of the Freda is about 500 feet. The boundary between the Freda and the underlying Nonesuch shale is transitional.

Jacobsville sandstone is primarily buff or salmon colored, fine to medium-grained sandstone with small amounts of reddish-brown pebble conglomerates, red shales, and silty shales. The sandstone has a large proportion of well-rounded quartz grains. This formation probably represents the last phase of the Keweenawan.

Intrusive rhyolite bodies of the Keweenaw are uniform, fine-grained rocks which are pale reddish-brown on freshly broken surfaces and white on weathered surfaces. The main minerals are quartz, orthoclase, and albite-oligoclase. The rhyolite is closely jointed and the bodies appear to be stocks. None are older than middle Keweenawan as they intrude the Portage Lake lava series. The dominance of rhyolite fragments in the beds of conglomerate in the lava series indicate that the rhyolite intrusive rocks, or extrusive rocks, must have been exposed over large areas during and after middle Keweenawan.

Structural Setting

The Michigan copper region is on the southern rim of the Lake Superior syncline or basin of Keweenawan age. The north limb of this syncline is found on the north shore of Lake Superior and on Isle Royale. Early Keweenawan rocks dip steeply (60°) and later ones progressively less steeply (down to 25°) northwestward toward the center of the basin.

Transverse to the general strike of the Lake Superior syncline are folds that pitch down the dip of the larger fold; among these folds are the northward pitching Keweenawan anticline with its crest near Keweenaw point, the Ontonagon sycnline immediately to the southwest, and the Bessemer anticline. On these broad, open folds (the distance from the crest of the Keweenaw anticline to the crest of the Bessemer anticline is about 110 miles) are several subordinate folds of similar character and trend such as Winona anticline, Firesteel River syncline, and Mass anticline. These are also broad, open folds but only 5 to 10 miles across as contrasted with 100 miles for the major cross folds. Some of the smaller folds show a rather uniform bending of the beds, with some faulting near the crest. Others, such as the Mass anticline, have beds bent sharply at the crests and at the margins of the folds, but the limbs are fairly straight.

At the Lake, South Lake, and Algomah mines there is a broad, gentle syncline (Lake syncline) and a narrow, steep anticline (Mass anticline) between the Keweenaw fault and the point where the rocks have the normal westerly dip. These folds are shown on the Algomah area map (Figure 3) and also indicated on the north-south structural section of the Algomah-South Lake area (Figure 4) and the east-west section at the Lake mine (Figure 5).

The greatest fault of the region is the Keweenaw fault, which bounds the Portage Lake lava series on the south from the end of Keweenaw point to Lake Gogebic. This is a reverse fault with a variable dip of 20° to 70° northwest, along which the lava flows have been thrust over the younger Jacobsville sandstone. The dip of the fault is nearly parallel to the flows and its

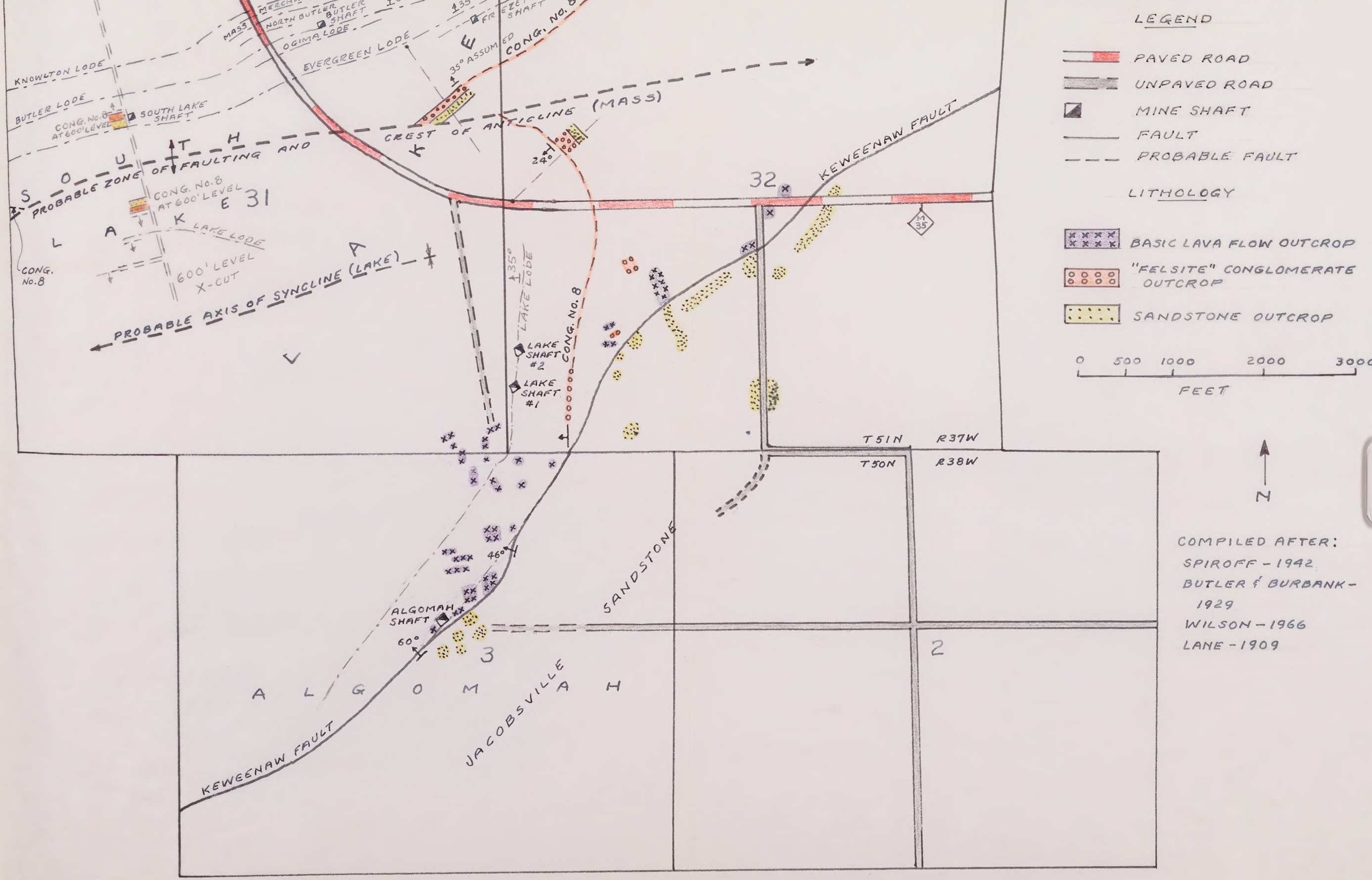
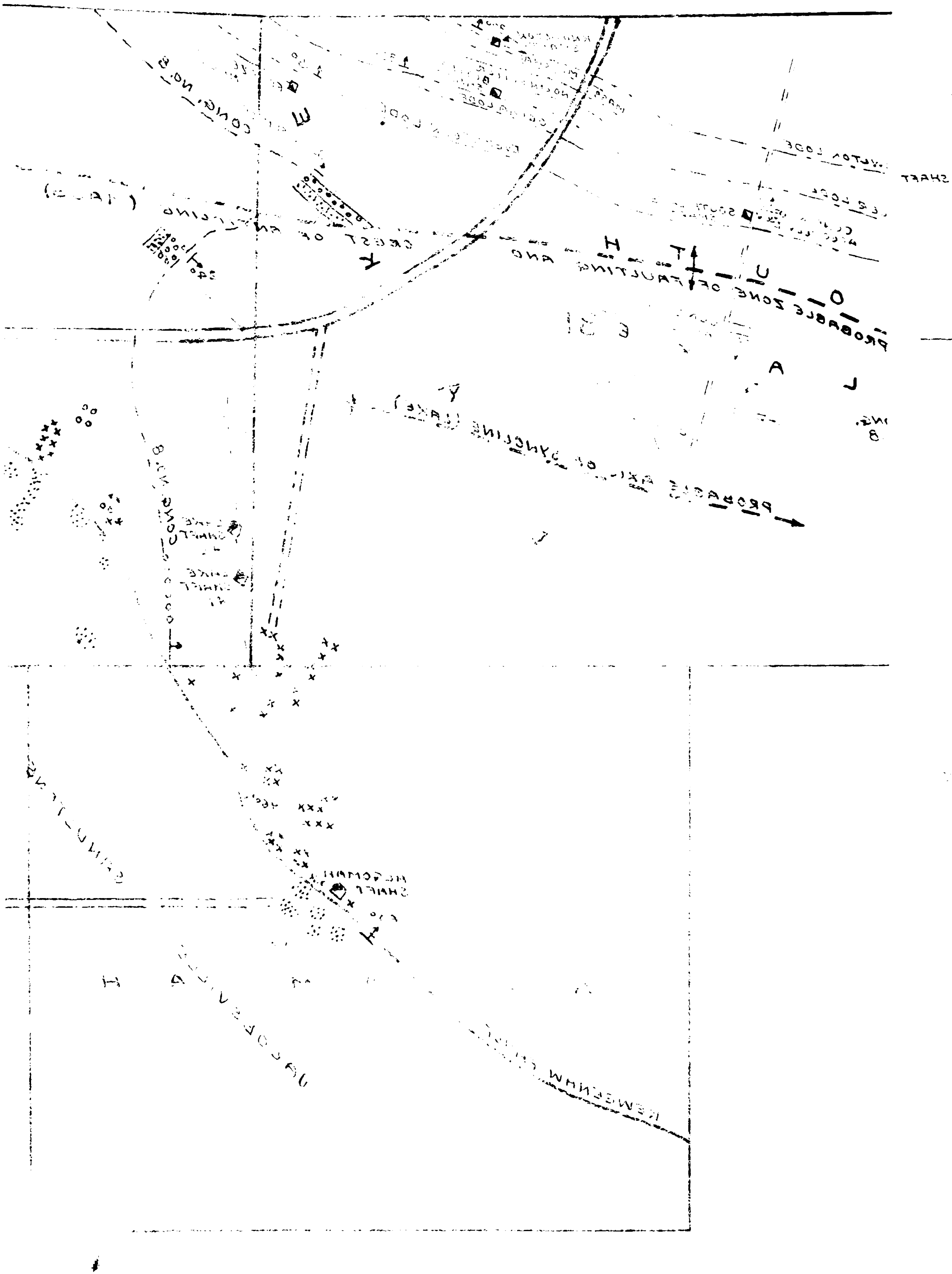
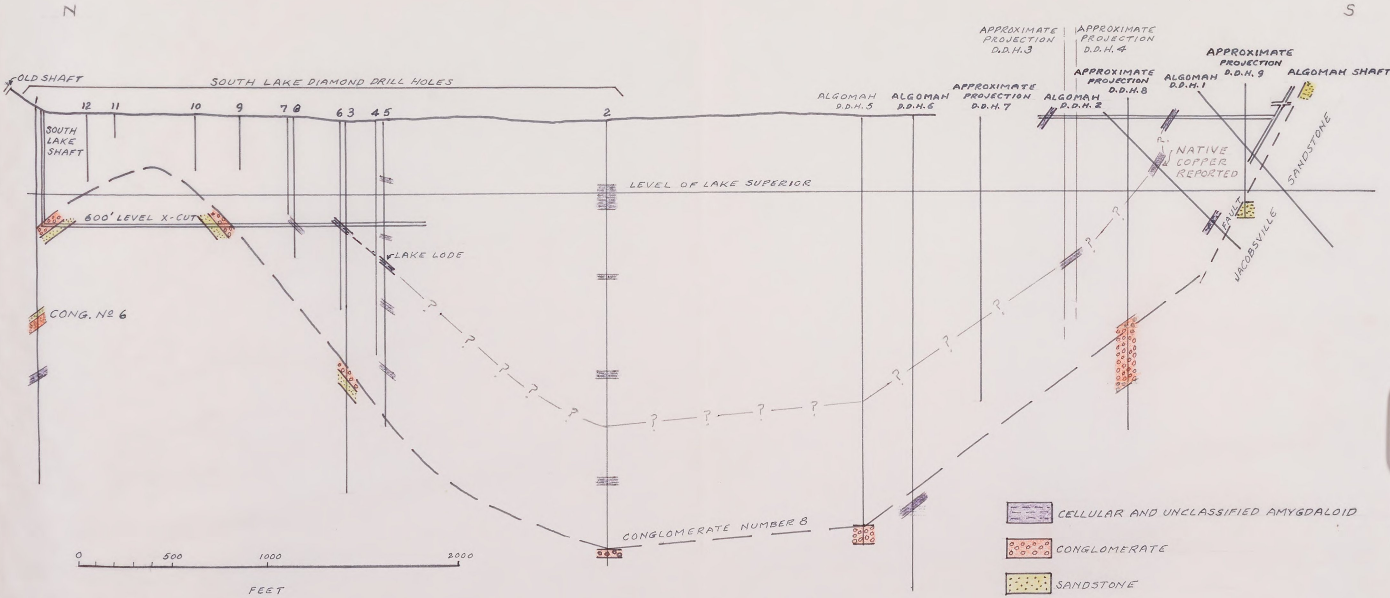


FIGURE 3
GENERAL GEOLOGY OF THE ALGOMAH MICHIGAN AREA



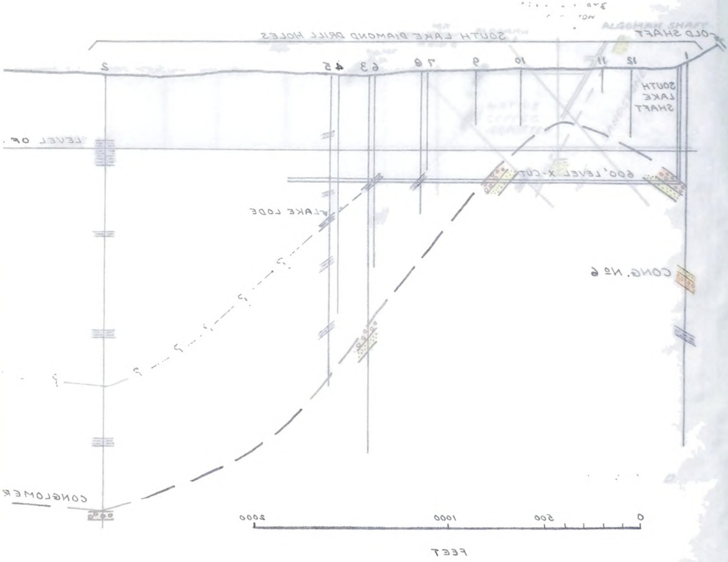
CONG. NO. 8
CREST OF ANTICLINE
PROBABLE ZONE OF FAULTING AND
PROBABLE AXIS OF SYNCLINE (LAKE)
JACOBSVILLE
KEWEENAW



SOUTH LAKE, LAKE, AND ALGOMAH SECTIONS T50N, R38W AND T51N, R37W

AFTER: BUTLER & BURBANK (1929), PLATE 30
ALGOMAH MINING COMPANY ANNUAL REPORT (1910), PAGE 2

FIGURE 4



SOUTH LAKE, LAKE, AND ALGOMAH S

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FIGURE 4

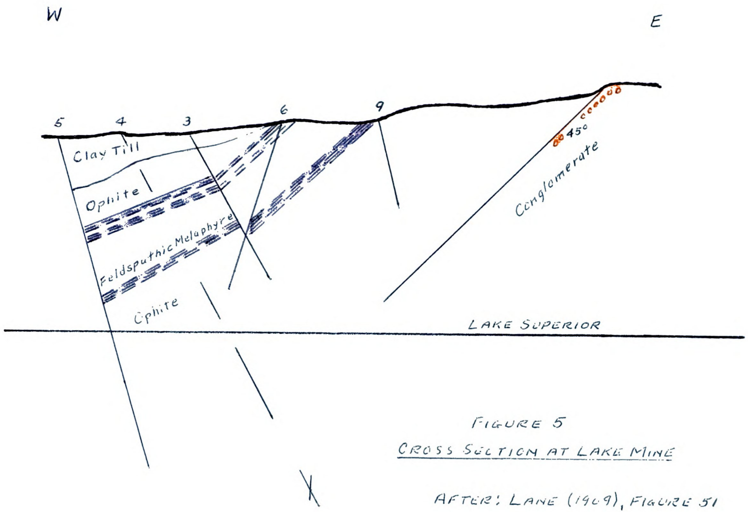
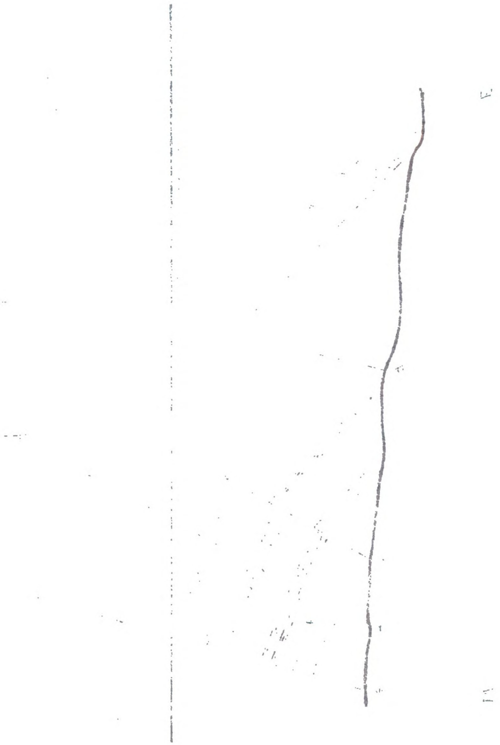


FIGURE 5

CROSS SECTION AT LAKE MINE

AFTER: LANE (1909), FIGURE 51



strike is generally northeast, varying as it follows the major anticlinal and synclinal structures of the rocks. In general, the northward-dipping lava flows on the hanging-wall side of the fault are bent downward so that in places the dip is reversed, and the flat lying sandstones on the foot-wall side are turned up rather abruptly.

Many branch faults and fissures are associated with the Keweenaw fault. Relatively small transverse faults and fissures, which apparently resulted during the folding of the rocks, are also present around the crests of the anticlines such as the Mass anticline. Most of the smaller faults in the peninsula strike northwest and are vertical or dip steeply northeast. The existence of these smaller faults is revealed by offsets in key horizons rather than by actual observations of the fault planes.

Economic Geology

The Michigan copper deposits are of two basic types, lode deposits and fissure deposits. The lode deposits consist of amygdaloid lodes, which are mineralized amygdaloidal or brecciated tops of lava flows, and conglomerate lodes, which are mineralized beds of conglomerate interbedded with the lava flows. The open textured material of a flow top is commonly called

amygdaloid. The most common of the several types of tops is the cellular top produced by the simple freezing of gas bubbles. Coalescing amygdaloid results when individual bubbles collect into irregular pockets of gas. Fragmental flow top is due to the breaking up of a cellular top due to movement during solidification. Scoriaceous flow top is the result of erosion of any of the other types of top. Most amygdaloidal lodes are fragmental in nature and very few mines have been found in the cellular amygdaloids. The fissure deposits are veins found along fractures in the beds. All fissure deposits are of narrow tabular form.

The mineable copper occurs in ore "shoots" which are far smaller than the lodes containing them. The ore in the "shoots" was deposited in the more permeable part of the lode by chemical solutions, the movement of which was controlled by relatively impermeable barriers.

In the area north of the Lake mine mining has taken place in a series of lodes, the base of which is about 400 to 500 feet above the Number 8 conglomerate. From higher to lower these lodes are the Knowlton, Merchant, Mass, North Butler, Butler, South Butler, Ogima, and Evergreen. The correlation of the individual lodes from development to another is uncertain but at each mine several lodes carried enough copper to have warranted development and a considerable amount of copper has

been removed from the series as a whole (Figure 3).

The flows of these lodes are intermediate in composition and texturally they are mainly melaphyres and glomeroporphyrites. The amygdaloids of this series of flows are quite commonly thick, coarse fragmental material rich in copper with smaller alternating lean areas which are thin and cellular or trappy and fragmental. Some of the lodes show a local tendency to pass into the amygdaloid of the coalescing type. The copper of these lodes is in small and large masses irregularly distributed throughout the lode. A large percentage of the copper found is quite coarse.

This series of beds is involved in the Mass anticline and the Lake mine syncline, but the correlation of the individual beds in the Lake mine syncline with the normally dipping beds to the north is somewhat uncertain. The Lake lode is a wide amygdaloid involved in the Lake mine fold. (Figure 6). The copper is irregulatly distributed along the Lake lode with the rich and poor portions alternating. Structurally this lode continues onto the Algomah property and this is confirmed by diamond drilling. However, it is not possible to correlate this lode with the Algomah lode although mineralization similar to that in the Algomah lode has been found in the second level of the Lake mine. Diamond drilling near the Algomah mine indicated the presence of an amygdaloid with

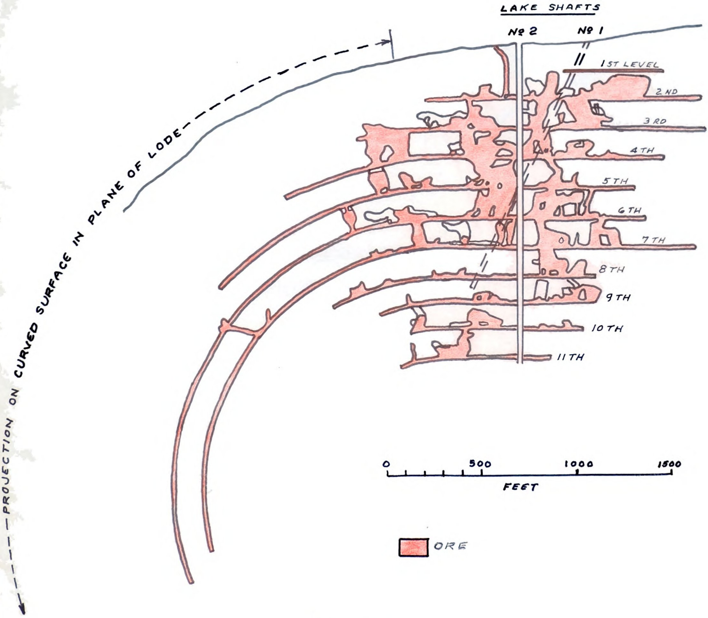
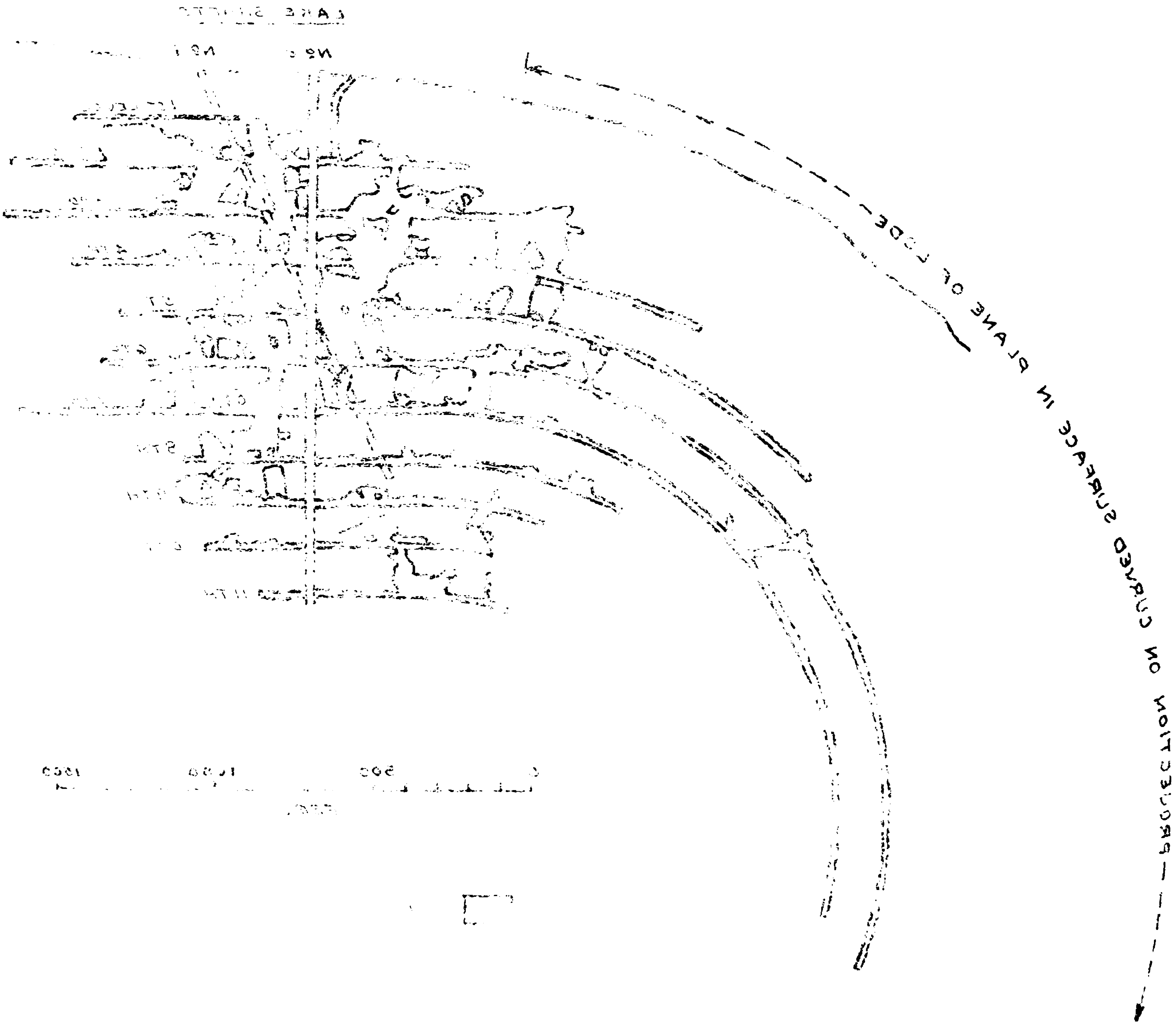


FIGURE 6

LONGITUDINAL SECTION OF LAKE LODE IN PLANE OF LODE



LONGITUDINAL SECTION OF LAKE LODE

IN PLANE OF LODE

native copper which might also be the Lake lode. This amygdaloid is about 400 feet above the Algomah lode. The Algomah lode itself is mostly cellular with some fragmental areas.

In the area there are faults and fissures that are associated with the Mass anticline that show a small amount of movement. Little information is available on these but most are mineralized and were evidently formed before the period of mineralization although there has been some movement on them since mineralization.

PROCEDURE

The field work for the study was accomplished in the summer of 1966. Since the area of outcrop is rather small, all outcrops were visited, mapped, and sampled. Pace and compass mapping was employed for the study. As the author was unable to go underground it was necessary to rely on personal interviews with former mine employees.

Thin sections were made of each outcrop to determine the mineral compositions and variations. Polished sections and thin sections were prepared of both high and low grade ores. These sections were studied using standard microscopic techniques.

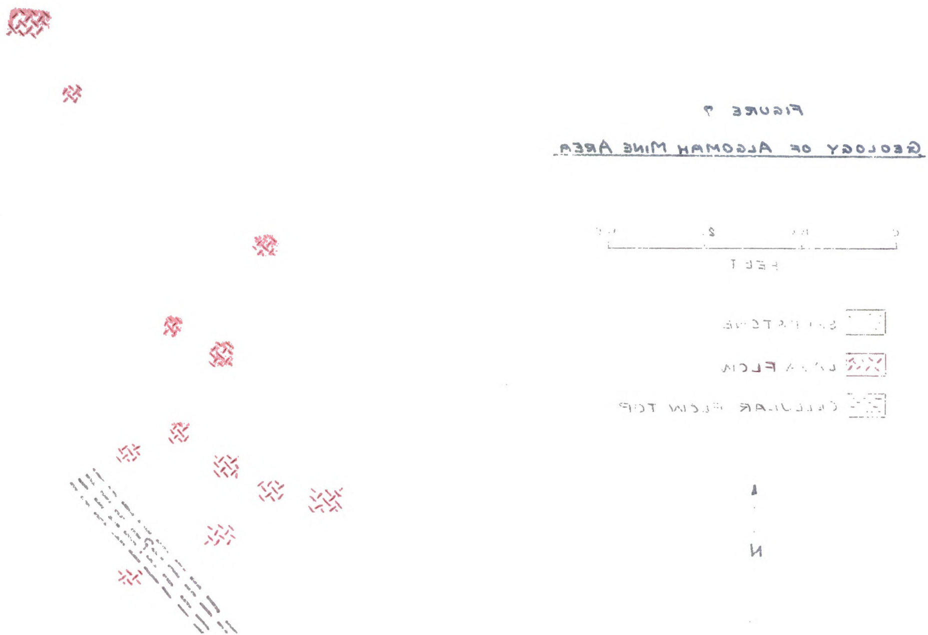
One chemical analysis was made to aid in the study of the ore mineralization.

FIGURE 7

GEOLOGY OF ALGOMAH MINE AREA

Figure

Geology of Algomah Mine Area



PETROLOGY

Sandstone

The sandstone of the Algomah area is a msaaive, white, weathered quartz sandstone which easily disintegrates in the hand-specimen. It was originally red in color due to the presence of iron oxide but today retains only a few streaks and spots of this original color. Evidently much of the matrix material and color have been leached from the rock. The main constituent of this sandstone is rounded quartz grains about ½ millimeter in diameter. Also present are a few large grains of granule size that appear to be metaquartzite or vein quartz particles.

In the outcrop it is very difficult to determine the orientation of the bedding of this sandstone because of its massive nature. However, it appears to weather along former bedding planes and the attitude of these apparent bedding planes indicates that this sandstone has been thrust into a nearly vertical orientation by the Keweenaw faulting in the area. This situation is very similar to that at the Natural Wall ravine near Calumet, Michigan, where the Keweenaw faulting has given the Jacobsville a similar orientation. The sandstone at Algomah is probably part of the massive facies of the

Jacobsville sandstone that was defined by Hamblin. (11)

In thin section this is a feldspathic sandstone composed mostly of subangular to rounded, unstrained quartz grains, most of which have strings of gas holes. A large number of the quartz grains present have been cracked, especially in the rocks nearest the fault zone, evidently by the faulting. Also present are a few granules of strained polycrystalline metamorphic quartzite. Orthoclase and plagioclase are present in smaller, but almost equal, amounts (Photo 2).

The feldspars occur as subangular to rounded grains with an occasional cleavage fragment present. A few grains of microcline and orthoclase have secondary overgrowths of orthoclase, while some of the plagioclase grains have albite overgrowths. These overgrowths tend to restore the regular crystal form of the mineral and are most noticeable when they occur on feldspar particles coated with iron oxide. Often cracks traverse the core and the overgrowth. Overgrowths are also seen on a few quartz grains and are made obvious by a small amount of opaque dust between the grain and the overgrowth.

Interstitial to the coarser grains in the rock are fine grained aggregates of quartz and microcline in a

11) Hamblin, W. K., The Cambrian Sandstones of Northern Michigan, Michigan Geological Survey, Lansing, Michigan, 1958, pages 42-44.

random orientation. The matrix material, most of which has been removed by weathering, seems to be made up of quartz and clay minerals. In a few places, such as the finer segments and where there is residual matrix material, it is possible to see remnants of the hematite stains, which had given this rock its original red color.

Photo 2. Jacobsville Sandstone Showing Microcline and Quartz. Crossed Nicols, X50.

A few accessories of heavy minerals are visible in thin section. The most prominent accessory is leucoxene, some of which shows iron oxide staining. Smaller amounts of ilmenite or titaniferous magnetite are present and are accompanied by leucoxene. A Few grains of apatite, sphene, and zircon with iron oxide staining are present.

The mode of this sandstone is:

Unstrained quartz	81.9%
Polycrystalline strained quartz	6.8%
Microcline	5.6%
Plagioclase	2.6%
Orthoclase	2.1%
Leucoxene	1.0%
Zircon, Apatite, Sphene	Trace
	100.0%

It is felt by the author that the sandstone of the Algomah area is definitely Jacobsville since is has the usual fault contact with the lave flows that is characteristic of the Jacobsville in the Keweenaw. Also this sandstone is very similar to the massive facies of the Jacobsville as defined by Hamblin (1958) at Victoria Falls 12 miles away. It is interesting to note that thin sections of the Algomah area sandstone compared almost identically with thin sections of Jacobsville from well known outcrops in Marquette, Michigan. The only petrographic differences noted were the removal of hematite stains and the shattering of the quartz grains in the Algomah sections.

Lava Flows

Parts of two flows outcrop in the Algomah area, the top part of the Algomah flow and the lower part of the flow containing the Lake lode(Figure 3). These flows are shown by petrographic and mining evidence to strike about N 40 E and dip about 60 NW in accordance with the structure of the Lake syncline (Figure 4). Mining work shows that much of the Algomah flow has been cut off by the Keweenaw fault in the Algomah area. Thin sections were prepared and studied of all outcrops of these flows in the area.

These flows are essentially ophitic basalts, which have been extensively altered. The essential minerals are plagioclase and pyroxene. Compositional variation as a function of flow position occurs noticeably. The plagioclase near the flow tops and bottoms is oligoclase ($Ab_{72}An_{28}$) and this changes gradually to andesine ($Ab_{52}An_{48}$) near the central part of the lava flows, as determined by the method of Michel-Levy. This is a reversal of the normal trend as indicated by the plagioclase cooling curve. There is no visible evidence of replacement in the plagioclases. Augite is the pyroxene in the flows and this mineral shows some variation with position although not as striking as that of the plagioclase. This variation is noted optically by a slight increase in color in the augite towards the flow center, probably resulting from an increase in the amount of iron in the mineral as a result of slower cooling. The amount of pyroxene decreases toward the flow top and no pyroxene is found in the topmost parts of the flows. The material that would form pyroxene is masked by ferric oxide (Photo 3).

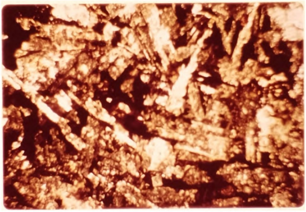


Photo 3. Flow Top. Only Plagioclase Laths are Visible. Crossed Nicols, X25.

All of the flow rocks sampled show extensive hydrothermal alteration. The most widespread secondary mineral seems to be chlorite alteration products of all minerals that retain, in some cases, the original rock texture (Photo 4). There is also some green-brown pumpellyite present.

What appears to have been early formed olivine grains have altered to iddingsite, while early pyroxenes have now completely changed to chlorite, green biotite, and some clinozoisite. All of these alteration products are associated with considerable iron oxide, mostly hematite. The plagioclase is heavily altered, in some instances it is practically impossible to determine its composition.

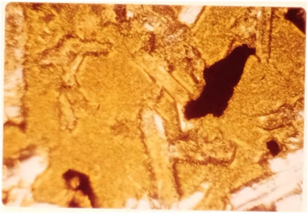


Photo 4. Chlorite Rock Alteration Consisting Mostly of Penninite with some Prochlorite. Crossed Nicols, X50.

Alteration products of the plagioclase are paragonite, iron-rich epidote (pistacite) with high pleochroism, and probably some clay minerals. The more basic plagioclases are more extensively altered. The magnetite has altered to hematite, and some leucoxene.

Texturally, it appears as if this rock had two phases in its cooling history. The first minerals to form were ferromagnesians, that have altered to chlorite, epidote-group minerals, and iron oxide, since the later minerals crystallized around these original crystals. Following these first formed ferromagnesians, plagioclase crystallized in a glomeroporphyritic arrangement, followed by pyroxenes that are fresh in the rock. The resulting rock has essentially an ophitic texture (Photo 5).

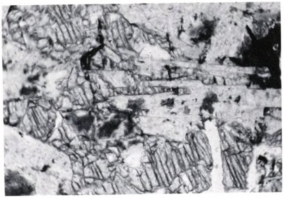


Photo 5. Pyroxene Enclosing Plagioclase.
Crossed Nicols, X50.

A description of a typical rock from the Lake lode flow is given here.

Sample A-21 (Lake lode flow) - In thin section this rock has a hypidiomorphic, holocrystalline, ophitic texture. The essential minenals are pyroxene and plagioclase.

The plagioclase is andesine ($Ab_{67}An_{33}$). It varies from fresh to heavily altered to paragonite and iron-rich epidote, with some iron oxide dust present. There is a tendency for the plagioclase to be glomeroporphyritic. The pyroxene of the rock is fresh augite. The augite is poikilitic with plagioclase inclusions and is pale green-brown in color.

Magnetite is present but most of it has altered to hematite. Most of this opaque material surrounds what appears to be an earlier formed pyroxene or olivine but has now altered completely to clinozoisite, green biotite, and chlorite.

Chlorite is present as a rock alteration. It is composes mainly of penninite with some prochlorite and contains some epidote and a few small patches of disseminated iron oxide. In places the original texture of the rock is preserved in this alteration. There are veins of chlorite cutting the entire specimen.

The mode of this rock is:

Andesine ------	45.8%
Augite --------	24.3%
Magnetite -----	3.3%
Hematite ------	5.3%
Biotite -------	.5%
Clinozoisite --	Trace
Penninite -----	9.0%
Paragonite ----	5.2%
Epidote -------	1.3%
Prochlorite ---	5.3%
	100.0%

The flow top exhibits a number of noticeable differences from the body of the flows, such as finer texture, more sodic plagioclase, gas holes, greater alteration, little or no pyroxene, and a larger percentage of ferric oxide. These differences are best shown by describing a typical sample from the Algomah flow top.

Sample A-9b (Algomah flow top) - In thin section this rock has a hypidiomorphic, holocrystalline, ophitic texture. The main minerals visible are plagioclase and chlorite.

The plagioclase is oligoclase ($Ab_{72}An_{28}$) which shows heavy alteration to paragonite and iron-rich epidote. Chlorite (penninite) present as rock alteration retains the ophitic texture of the rock. No pyroxene is visible, although it may by masked by iron oxide as commonly occurs in the flow tops. Some magnetite is present but most of it has changed to hematite and leucoxene. Chlorite and clinozoisite with iron oxides may represent an original ferromagnesian mineral.

Gas holes in the rock have been filled with a number of minerals in a layered arrangement. (Photo 6). The outermost mineral is prochlorite, while the center is filled with radiating fibers of penninite and pistacite. Between the inner minerals and the prochlorite some of the vesicles have a thin layer of a colorless mineral that the author feels is a zeolite, probably chabazite.

The mode of this rock is:

Oligoclase ----	60.1%
Paragonite ----	5.1%
Epidote -------	.6%
Chlorite ------	18.1%
Magnetite -----	4.2%
Hematite ------	9.6%
Leucoxene -----	1.2%
Clinozoisite --	.8%
	99.8%

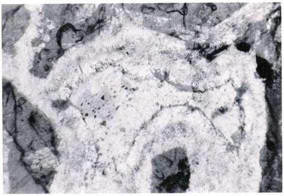


Photo 6. Gas Hole Filled with Secondary Minerals. Crossed Nicols, X50.

Ore

The ore at Algomah consists of essentially concentric bands of cupric oxide, and chrysocolla occurring in the vesicles of the cellular top of the Algomah flow. The flow top in the vicinity of this copper mineralization is heavily oxidized so that in thin section all of the rock-forming minerals except the plagioclase laths are masked by ferric oxide.

The ore mineralization at Algomah has been studied by Williams (1962a, b) in some detail using museum quality specimens. From a study of a number of polished sections the author concurs for the most part with the findings of Williams and will attempt to add to his work. Williams describes the ore mineralogy as follows:

"If all of the copper minerals found at the Algomah mine are listed in sequence the paragenesis is as follows: (oldest to youngest) native copper - cuprite - dioptase - paramelaconite - plancheite - atacamite - paratacamite - nantokite - tenorite - malachite - chrysocolla. Native copper and cuprite are both rare and both are commonly enclosed by later paramelaconite which may pseudomorphose cuprite. Tenorite, which directly replaces paramelaconite is in places cut by veinlets of later paramelaconite, which, in turn, shows incipient alteration to a second generation of tenorite. The atacamite, which occurs as large bladed crystals, commonly is replaced by twinned aggregates of paratacamite crystals. Nantokite occurs as microcrystalline material that embays the paratacamite; nontokite was not observed as a direct replacement product of atacamite." (12)

In his second article describing the Algomah minerals he states that:

"The matrix of the specimen contains small blebs of cuprite which are ringed by tenorite and then chrysocolla." (13)

This description is very similar to that of Koenig (1902) when he named the copper oxide "mineral" melanochalcite:

"The nodules' nucleus is formed by granular cuprite, with occasional druses, the later lined with octahedral crystals. This kernel is surrounded by a zone of pitchy-

12) Williams, S. A., op. cit., 1962a, page 111.

13) Williams, S. A., "Paramelaconite and Associated Minerals from the Algomah Mine, Ontonagon County, Michigan", American Mineralogist, Volume 47, 1962b, page 778.

black mineral, a few millimeters in thickness. Upon this follows a banded green zone of chrysocolla and malachite." (14)

Melanochalcite was later shown by Hunt and Krauss (1916) to be essentially a mixture of tenorite, chrysocolla, and malachite.

The concentric arrangement of minerals noted by Williams at Algomah was studied by the author in polished section. A pitchy-black material was noted in some instances between the tenorite and chrysocolla. This material appears to have the properties of melanochalcite or "copper pitch ore" as described by previous workers. Therefore, a chemical analysis was performed on a sample of this pitchy material that was separated from the other ore minerals under the microscope. The results of this analysis are included in Figure 8 as column 8. This analysis indicates that the ore mineral mixture melanochalcite is present at Algomah as would be expected, and microscopic examination indicated that it forms an appreciable amount of the ore minerals. Perhaps, since he makes no mention of such a mixture being present, Williams has assigned melanochalcite to what he calls "massive paramelaconite".

The chemical analysis of the melanochalcite from

14) Koenig, G. A., "On the New Species Melanochalcite and Keweenawite", American Journal of Science, Series 4, Volume 14, 1902, page 404.

SAMPLE / OXIDE	1	2	3	4	5	6	7	8
SiO_2	29.51	17.95	7.80	4.31		24.64	5.75	14.65
Al_2O_3						3.10		6.07
Fe_2O_3	.64	50.85	.07	.22	4.00	1.73	4.40	
FeO								.27
CuO	84.22	12.12	76.88	88.94	28.60	33.68	62.30	67.22
CaO	.36					.84		Trace
ZnO	.25		.41	.12	8.40	Trace		Trace
MnO	.28				21.20	19.19		.04
MgO								Trace
Na_2O								1.05
K_2O								.21
H_2O	6.99	20.55	7.71	4.48				8.40
CO_2	5.17		7.17					1.94
Insol.					22.80			
Ignit.					13.70	17.76		
TOTAL	100.78	101.47	100.04	99.85		100.94		99.85

Figure 8. Chemical Analyses of Selected Samples of Melanochalcite. Columns 1-7 Material From Southwest United States. Column 8 was Added by the Author Using Algomah Material. (15)

15) Guild, F. N., "Copper Pitch Ore", American Mineralogist, Volume 14, 1929, page 315.

Algomah has a rather high percentage of aluminum and sodium when compared with the analyses from other areas. This may be the result of copper mineralization replacing a sodium-aluminum zeolite vesicle filling.

The only other addition that can be made to the work of Williams concerns the mineralogy of the flow top. In a number of instances chrysocolla has replaced plagioclase laths in the rock. Schwartz (1934) states that this is a common occurrence in oxidized copper deposits of this type.

Interpretation

There are a number of factors which must be considered in interpreting the results of the present study of the Algomah mine. These factors are: (1) reversal of the normal plagioclase composition trend in a lava flow, (2) the unique mineralogy present, (3) the extreme leaching of the Jacobsville sandstone, and (4) the proximity of the Keweenaw fault and the isolation of a segment of the Algomah flow by the fault.

Since the Keweenaw lava flows are not oceanic, the spilitization of the plagioclase in the flow tops is indicative of post consolidation effects, probably closely associated with the copper mineralization. Studies by the writer of the Greenstone flow at Phoenix, Michigan, which is noted for its lack of copper mineralization, indicates that here the plagioclase is calcic at the base and that it shows the normal tendency to become more sodic towards the central portion of the flow. Therefore, the spilitization of the plagioclase in the flow tops tends to indicate that copper mineralization was associated with fluids containing considerable sodium, since the copper mineralization is essentially localized in the flow tops where spilitization occurs.

The presence of chlorides in the suite of supergene copper minerals at Algomah indicates that there must have been appreciable amounts of chlorides in the water. Mine waters of the Keweenaw are noted for their high concentrations of chlorides. However, the chloride concentration at Algomah did not have to be excessive since higher partial pressures of oxygen present during the supergene alteration greatly expanded the copper chloride stability field as shown by Williams (1962a). These facts indicate that the supergene copper deposition was from sodium chloride rich waters.

A possible, yet little considered mechanism involving Precambrian salt deposits in the vicinity of the magma chamber for the deposition of Keweenawan native copper would easily account for the presence of appreciable concentrations of sodium and chloride ions in the vicinity of the copper deposits. Trow (1966) indicates that reactions of the following nature may possibly explain what would take place if silica rich hydrothermal solutions, containing sodium chloride from a Precambrian salt bed were to interact with basic rocks containing a mineral or minerals such as cupiferous olivine.

(1) Halite + Silicon + Cupiferous Olivine + Labradorite $\longrightarrow$
$10NaCl$ $11Si^{+4}$ $Fe\text{-}Cu\text{-}SiO4$ $10NaAlSi_3O_8$ $10CaAl_2Si_3O_8$

Ferric Chloride + Cuprous Chloride Complex + Quartz
$FeCl_3$ $CuCl_2$ $2SiO_2$

Albite + Calcium + Aluminum + Chloride
$20NaAlSi_3O_8$ $10Ca^{+2}$ $10Al^{+3}$ $5Cl^-$

(2) $FeCl_3 + 3H_2O \longrightarrow Fe_2O_3 + 3HCl$

The albite and hematite would be left in the underground magma chamber and solutions containing NaCl, $CuCl_2^-$, Ca ^{2}, Al ^{3}, Cl^-, and SiO_2 then moved up the fault channelway to react and deposit the copper in the flow tops by cooling, decrease in pressure, and dilution by ground water. The various ions present would aid in the formation of quartz, chlorite, epidote, pumpellyite, and clinozoisite in the wall rock, along with spilitization of the plagioclase present. The calcium ions eliminated during spilitization could very possibly account for the calcite which is so common in the copper mineralized flow tops. In addition, such a mechanism would account for the presence of chloride rich mine waters. A variation of this mechanism suggested by Davidson (1965) would call for sodium chloride to be carried down to the magma chamber from above by deep circulating brines.

Supergene mineralization at Algomah also bears consideration. A wedge of the Algomah flow is isolated, since the permeability of the flow top is much greater than that of the basalt, and thrust to the surface by the Keweenaw fault in the area studied. Therefore, considerable surface water charged with carbon dioxide was available to mingle with the chloride rich waters which were held in the isolated flow top. Under such conditions cupric oxides can form native copper via cuprite if the log of the partial pressure of oxygen is greater than -37.9. This partial pressure is within that of normal surface water. If cuprite were to persist metastably under such oxygen pressures the field of the copper chlorides would be expanded so that they would form under the Algomah conditions. Under surface conditions of high partial pressure of oxygen and a high partial pressure of carbon dioxide of $10^{-3.5}$ malachite would form. The copper silicates here could have resulted by silica precipitation because of the presence of the electrolytes.

To interpret fully the supergene mineralization at Algomah it is necessary to study the inter-relations in the copper systems such as CO_2 - Cl_2 - O_2, CO_2 - Cl_2 - O_2 - SiO_2, which is beyond the scope of this paper. The hypothesis of copper being carried as a cuperous chloride complex also needs laboratory and thermodynamic study which also exceeds the breadth of this thesis.

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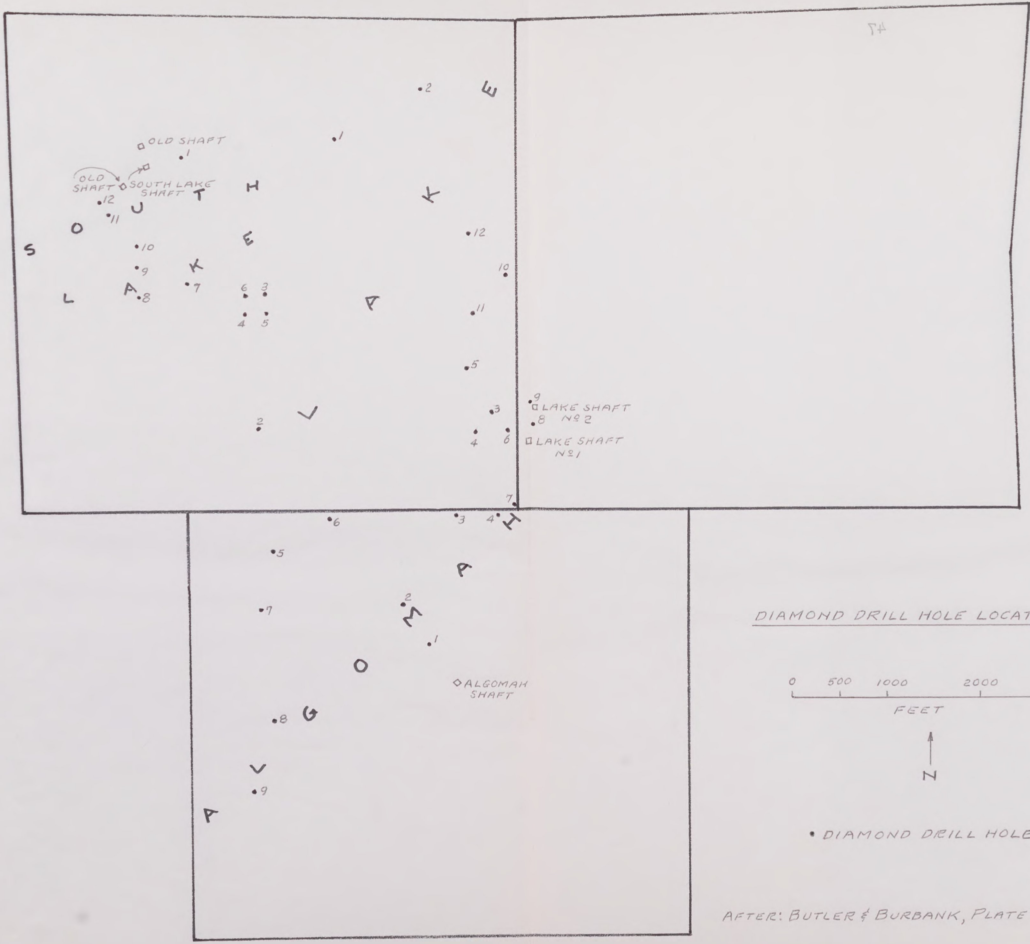
APPENDIX A

Location of Diamond Drill Holes



DIAMOND DRILL HOLE LOCATIONS

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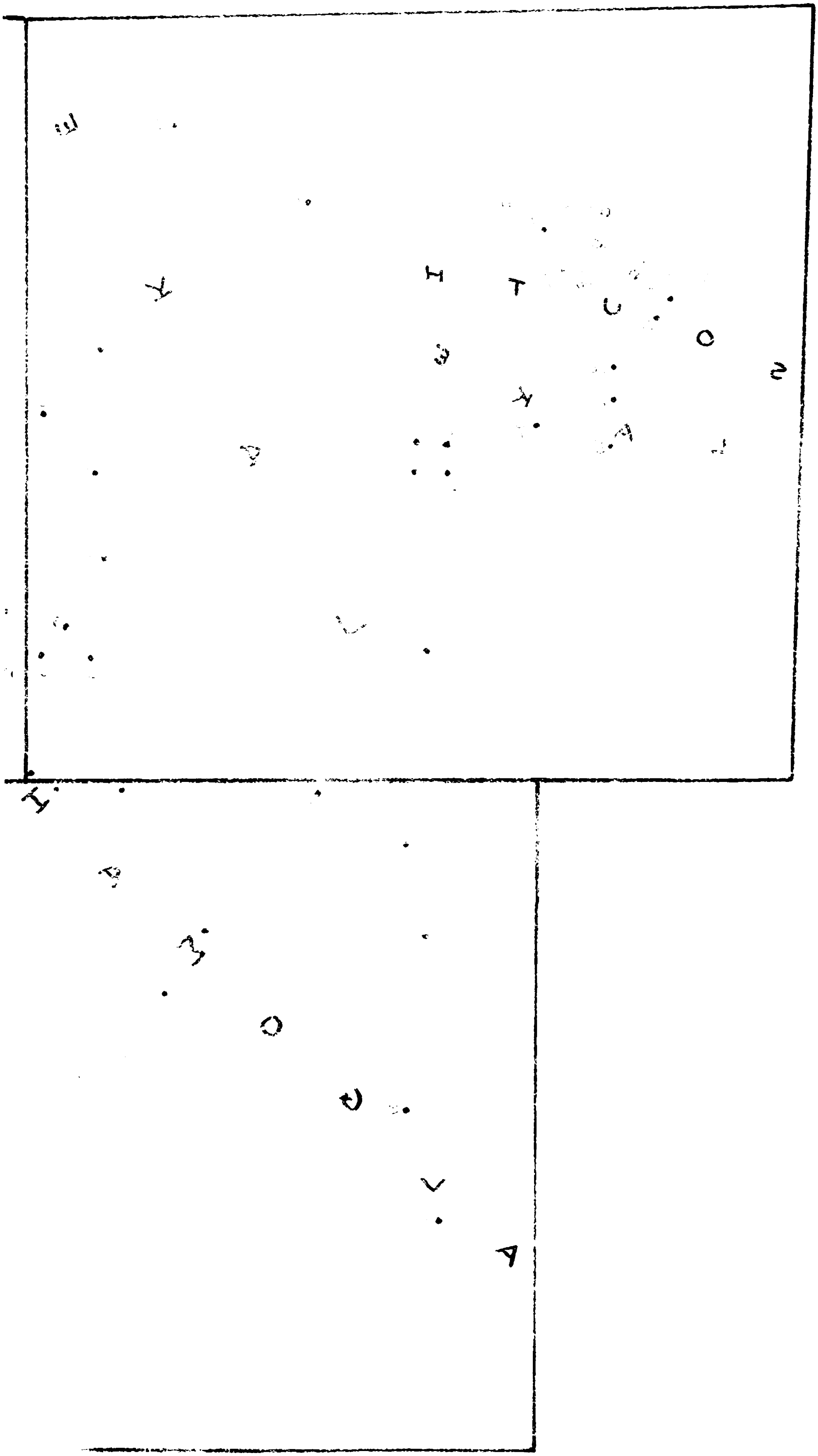
• DIAMOND DRILL HOLE

AFTER: BUTLER & BURBANK, PLATE 12



APPENDIX B

Algomah Diamond Drill Core Information

"Two diamond drill holes: viz: No.1 and No.2 were put down on the line of the shaft, one of these cutting the lode at a depth of 500 feet and the other at 800 feet. Both showed the lode from thirty to forty feet thick, but no native copper was seen in the cores from this lode. No. 2 hole cut an amygdaloidal bed about 400 feet above the main lode from which very little solid core was taken, but the cuttings showed considerable fine copper, and several nuggets of native copper were obtained. Two more diamond drill holes: viz: No. 3 and No. 4, were put down immediately adjoining the Lake Mine boundary. They both cut the Lake lode but no native copper was found in the cores. No. 3 showed some copper ore similar to that found at the Algomah shaft indicating a connection between the lodes. No. 5 drill hole is now being put down at a point shown on the accompanying maps, which also show the location of other drill holes and the shaft." (16)

"In addition to the work at the shaft, exploration has been carried on during 1911 on other parts of the property by diamond drilling. Two vertical holes were put down as far as possible, No. 5 to 2,241 feet and No. 6 to 2,538 feet. There are several lodes cut in

16) Algomah Mining Company Annual Report, 1910, page 2.

No. 6 hole, one at 2,090 feet, 2,090 to 2,119 feet being particularly promising." (17)

17) Hore, R. E., "The Copper Industry of Michigan", Mineral Resources of Michigan, 1910, Publication 8, Series 6, Michigan Geological and Biological Survey, Lansing, Michigan, 1912, pages 67-68.