

THE CLEVELAND-CLIFFS IRON COMPANY

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THE MARQUETTE MINERAL DISTRICT, MICHIGAN

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General Setting

The Marquette Mineral District of Michigan is situated in Marquette County and the east central part of Barage County. It was the first of the Lake Superior iron districts to be discovered and mined; and iron mining continues to be the major mining activity to this date. There has also been some production of gold. Figure 1 shows the outlined location of the Negaunee iron-formation, the principal host rock for the iron ore. Geographically, the Marquette District is located on a topographic highland rising some 600 to 1200 feet above Lake Superior (mean sea level elevation +602 feet). The average ground elevation near the mines at Ishpeming and Negaunee is +1400 feet. Firetower Hill in the Tilden Mine area rises to +1875 feet. Locally, the topography is rugged, with numerous lakes and swamps. The watershed drains both to Lake Superior and Lake Michigan from the Marquette highland. By tradition, in the Lake Superior Region, the topographic highs in which most of the iron districts are found are called "ranges"; hence the designation, the Marquette Iron Range. The three principal cities are Marquette (County seat and port), Ishpeming and Negaunee. Forest products, education (Northern Michigan University) and tourism augment mining in the area's economic activity.

Historical Setting

The first miners in the region may have been the pre-historic Indian copper miners some 3800 years ago (Drier and DuTemple, 1961). We know that the French explorers, Brule and Grenoble, visited the Upper Peninsula in 1622. They were followed by fur traders, missionaries and voyageurs. In 1668 Father Jacques Marquette and Father Claude Dablon established the mission at Sault Ste. Marie (Soo). It is believed that Father Marquette visited the site of the City of Marquette in 1670 and 1671 and used a campsite at Lighthouse Point. His name was given to the city, county and iron range in

honor of his early work here, as well as his extensive efforts in other parts of the north central states. He assisted Fathers Allouez and Dablon in making the first map of the Lake Superior Region, published in 1672 in Paris. Sporadic fur trading marked the next 170 years in this vicinity.

Michigan became a State in 1837. Dr. Douglass Houghton, the first State Geologist, convinced the State Legislature that the Federal Land Subdivision Survey should have geological mapping as an adjunct. The Indian Treaty of LaPointe, 1842, opened the Upper Peninsula to the white men. On September 19, 1844, a Government Survey Party under Mr. William A. Burt was running the east line of Section 1, T. 47 N. and R. 27 W. (Mather Mine "B" Shaft property). A younger brother of Douglass Houghton, Jacob, noted erratic compass behavior. They sought the cause and found, as recorded by Douglass Houghton, "Spathose and magnetite ores abounding." Later, in 1846, Burt wrote: "It may be reasonably inferred that not more than one-seventh of the number of Iron ore beds were seen during the survey of the Township lines; and if this district of Townships be subdivided with care in reference to mines and minerals, six times as many more will probably be found. If this view of the Iron region of the Northern Peninsula of Michigan be correct, it far excels any other portion of the United States in the abundance and good qualities of its Iron ores."

Word of the iron ore discovery spread through the state and elsewhere during that winter. In 1845 a group of men from Jackson, Michigan, formed the Jackson Mining Company. The treasurer, Philo Everett, and his associates, reached Teal Lake in June. The story is told that the Indian chief, Marji-Gesick, showed them the high grade hard ore under the stump of a fallen pine tree. By 1846, there were 106 mining companies. The first ore shipped consisted of six barrels on July 7, 1852. After the Soo Locks opened in June, 1855, Lake Superior iron mining boomed - a tribute to the farsighted vision of Douglass Houghton.

Since much of the ore was found at or near surface, the early mines were worked by open pit methods, as shown in Figure 2. As the mines went deeper, inclined skip roads were used to bring the ore to surface. By 1880, most of the ore was produced from underground workings. Early methods were open stoping, room-and-pillar stoping, and square-sets, followed by top-slicing in 1890. Sub-level caving was used where conditions permitted. Large scale block caving was introduced in 1950. Figure 3 illustrates a sub-level stoping scene.

Emphasis in mining was placed on the high grade direct shipping ores. However, in the 1880's several attempts were made to use concentrating plants. Thomas Edison built a magnetic separator at Humboldt in 1888. It produced 893 tons of high grade concentrate before it burned in 1889. After World War II, the mining companies worked on developing economic processes of con-

centrating the low grade Negaunee iron-formation, also called "jasper" or "taconite." The first commercial plant, opened in 1954, was the Humboldt Mine of The Cleveland-Cliffs Iron Company and Ford Motor Company. The Republic Mine was opened in 1956, and the Empire Mine in 1963; both partnerships of various steel companies and Cleveland-Cliffs. All three open pit properties produce high grade pellets.

The Marquette Iron Range is made up of three districts (see Figure 4). From 1852 through 1963, the iron ore production from these districts was:

Principal district	291,323,507
Cascade district	17,895,700
Gwinn district	<u>12,785,260</u>
Total	322,004,467 long tons

Of the total of 291 million tons produced from the principal part of the Range, 4,266,858 long tons were from the Bijiki iron-formation, and the balance was from the Negaunee iron-formation.

Concentration was accomplished on the Bijiki iron-formation by using the heavy media process at the Ohio Mine. From 1952 to 1960, a total of 745,620 long tons of concentrate was produced from several open pit operations.

Not all Marquette Range ores were shipped to the blast furnaces. Local charcoal furnaces, used from 1857 through 1893, produced an estimated one and a half million tons of pig iron.

Geologic Setting

The principal rock units are Precambrian in age. Structurally, they are assigned to the Southern Province of the great Canadian Shield (Leech et al, 1963). Probably they were subjected to the major orogenies of the Kenoran and Penokean (Hudsonian, Stockwell, 1962), as well as more local deformation.

The thick sedimentary series in which the iron ore is found was called Huronian by Whitney in 1857, and the term was used for the next century. James (1958) pointed out that the series differs considerably from the type section of the Huronian of Ontario and is more firmly correlated with the Animikie series of northeastern Minnesota; therefore, the United States Geological Survey uses the term Animikie. Goldich, et al (1961) dated the Animikie as middle Precambrian in age. By Canadian practice, Stockwell (1962) would term Animikie as Lower Proterozoic.

The Animikie series is found in a long westward plunging synclinorium which opens to the west (see Figure 4). Near the Baraga County line, the south limb of the major syncline has been folded into a lesser downfold called the Republic Trough. The sedimentary series continues into Baraga, Dickinson and Iron Counties. Older (Archean) rocks are found to the north of the synclinorium. To the south is a granite complex, thought to be related to the folding of the synclinorium against the older rock buttress to the north.

The Cascade Range, immediately to the southeast of the Marquette synclinorium, is considered to be a faulted segment of the main structure. The Gwinn or Swanzy area, some 20 miles southeast of Negaunee, and the Dead River area, a few miles north of the Marquette Range, are separate basins, thought to contain rocks of the Animikie series. The entire district has been intruded by rocks of Keweenawan age. Cambrian and Ordovician sandstones and limestones are found to the south and southeast. The district was glaciated extensively.

Stratigraphic Column

A schematic summary of the stratigraphic column is shown as the legend on Figure 4. This column is a modification of the most recent work by the United States Geological Survey, together with data from the mining companies' drill hole and underground and surface exposure information. Figure 4 is a plan map indicating the principal Animikie and older rock units which make up the Marquette synclinorium and environs. Figures 5 and 6 illustrate spatial relations of the principal rock units in the vicinity of Negaunee and Ishpeming. Figure 7 indicates the relative thicknesses of the stratigraphic units from east to west in the synclinorium. Variations reflect several features such as the extent of primary sedimentation and later erosion. Apparently the locus of the sedimentation moved westerly as the younger rocks were being deposited.

Pre-Animikie Basement Complex

Both Monographs 28 and 52 describe the Mona and Kitchi schists which were called Keewatin metasediments and metavolcanics. They were intruded by "Laurentian" granites, now represented by granites and gneisses.

Recent detailed mapping by the U.S. Geological Survey (Gair et al, 1963, et seq.) has found that the Mona schist consists of schistose and massive metabasalt, actinolitic and chloritic schists, ellipsoidal greenstone, chloritic slate and felsite. This thick series is intruded by tonalite and granodiorite, with

some monzonite, quartz monzonite and granite. The dikes and sills cutting the Mona schist are felsic porphyry, frequently weathering to a pale pink color. A widespread unconformity separates all these rocks from the Animikie series.

Animikie Series

Chocolay Group

Three formations make up the Chocolay Group of lower Animikie sediments. The basal unit is the Mesnard quartzite, which is a vitreous, medium-grained, thin to thick bedded quartzite, locally brecciated, with cross-bedding and ripple marks. Near Enchantment Lake, about 4 miles southwest of Marquette, the basal portion is made up of conglomerate, graywacke, arkose, and sericitic slates and quartzites although not all of these types are found in the same location.

The Kona dolomite overlies the Mesnard formation and is the thickest and most extensive member of the Chocolay Group in the area between Marquette and Negaunee. It is principally a light-colored fine to medium-grained massive dolomite. Locally it has thin laminated chert layers, sericitic slate, quartzites and laminated siltite. In places the dolomite is extensively silicified. Recent mapping (Fritts, 1964) identifies some quartzitic areas as Kona, rather than Mesnard as mapped earlier. Gair et al (1961) describes the silicification of the Kona dolomite as follows: "Silicified Kona dolomite most typically consists of thick laminated masses of fine-grained quartz (chert). The laminations are reddish or bluish black to white, depending on variations in minor amounts of different iron oxides from layer to layer. Massive siliceous rock consisting of fragments of white chert in a reddish-brown hematitic cherty matrix apparently resulted from post-brecciation silicification of the dolomitic portion of laminated cherty dolomite. Thin sections of silicified dolomite generally show a fine-grained mosaic of cherty quartz with small loose clusters of very fine-grained carbonate particles." Not only the dolomitic portions of the Kona have been silicified but also the slates and quartzites have been impregnated and cut by numerous quartz veins.

Another distinctive feature of the Kona is the presence of the algal structures, which occur widely throughout the Kona although they are not confined to any given horizon. Algal structures are locally associated with oolites, which confirms their shallow-water origin (Gair, 1962, oral communication).

The uppermost member of the Chocolay Group is the Wewe slate, which has an estimated maximum thickness of nearly 900 feet. It is a gray to greenish-gray, laminated to massive slate, with interbeds of impure dark quartzite. A

conglomerate is found locally. Elsewhere, the Wewe is brecciated and impregnated with quartz and specular hematite. In places the rock has textures which suggest the presence of volcanic and pyroclastic materials (Gair, 1962, oral communication).

Seaman (1944) assigned the Wewe to the upper Kona; Boyum (1954, 1963) followed the same practice. This report reflects the recent U. S. Geological Survey mapping and re-instates the Wewe as a distinct formation.

Menominee Group

The Menominee Group is named for the Menominee district of southern Dickinson County. James (1958) assigned this name to the middle Animikie rocks of the Marquette Range comprising the Ajibik, Siamo and Negaunee formations. There appears to be an erosional disconformity between the Chocoy and Menominee Groups.

The Ajibik quartzite is vitreous, medium-grained, thin to thick bedded, with some sericitic to chloritic slate. A basal conglomerate is found in Section 6, T. 47 N., R. 25 W., and elsewhere.

The Siamo slate formation contains laminated to massive dark gray and gray-green slates, argillites, graywacke and impure quartzite. Characteristically, the slates weather brownish or reddish.

Tyler and Twenhofel (1952) described the Goose Lake iron-formation, which is a magnetic member of the Siamo formation. Its thickness is estimated at 50 to 100 feet. It extends for some distance along the strike west and northwest of Goose Lake (Gair and Wier, 1964). The iron-formation is laminated, magnetic, cherty, chloritic and sideritic. The iron-formation at the St. Lawrence pit in Section 5, T. 47 N., R 27 W., is thought to be Goose Lake, also.

The Palmer gneiss was described in detail by Lamey (1935). He concluded that the Palmer gneiss represented metamorphosed (Animikie) sediments, principally the Ajibik and Siamo formations, and locally the Mesnard and Kona formations. Monographs 28 and 52 describe the Palmer gneiss as a belt of Laurentian rocks, with the comment that "phases of it look like metamorphosed sediments." Future mapping may clarify these relationships.

The Negaunee iron-formation is the most important and interesting member of the entire column, as it is the host rock for most of the iron ores. In general, it is similar to other Animikie iron-formations of the Lake Superior Region. The maximum stratigraphic thickness is attained in the Negaunee-Ishpeming area where it exceeds 2,000 feet, not including the intrusive masses. It is remarkable also for its relative lack of argillaceous and arenaceous facies.

The lithology is discussed in more detail later in this summary.

Baraga Group

The Baraga Group consists of two major members: the Goodrich and the Michigamme formations. The Goodrich formation is principally quartzite, with interbedded argillites and conglomerates. In most localities, there is a basal conglomerate made up of fragments of the Negaunee iron-formation. The Negaunee-Goodrich contact is reported to have up to 15° angular discordance, but commonly there is little noticeable discordance.

Overlying the Goodrich quartzite is the thickest member of the entire Animikie Series, the Michigamme formation which probably exceeds 5,000 feet. It is distinctive also in its areal extent, not only in the Marquette District, but over much of the central part of the Upper Peninsula.

Near the base of the Michigamme formation is a thin magnetic sub-member, termed the Greenwood formation by Swanson and Zinn (1930). Most of the Michigamme is slate, argillite and graywacke. The Clarksburg pyroclastics are found in the lower portion of the Michigamme where they occupy an asymmetrical position in the synclinorium (see Figure 4). The Bijiki iron-formation is found above the middle member of the Michigamme. It extends from north of Humboldt, at the Bessie Mine, to west of Three Lakes. Over 4 million tons of iron ore have been produced from mines in the Bijiki.

Harold James (1958) in the U.S.G.S. Professional Paper 314-C, describes the Paint River Group that overlies the Michigamme formation. These rocks are found to the southwest of the Marquette Mineral District. In the past, some geologists have correlated the Bijiki iron-formation with the Riverton iron-formation of the Iron River-Crystal Falls iron districts. This would mean that part of the Michigamme formation would be in the Paint River Group.

Granite is the principal rock type along the south limb of the Animikie synclinorium. There are thought to be both pre-Animikie and post-Animikie granites. Goldich determined an age of 1,900 million years on one sample south of Republic, and 1,600 million years on another. Some students believe that a portion of the granite-appearing rocks were formed by granitization of pre-existing Animikie sediments.

Seaman (1944) suggested periods of orogeny following Michigamme time which he called the Sibley and Superior or Republic, preceding Keweenaw time. This would correspond to the Penokean (Goldich et al, 1961) and may be the time of the post-Animikie granites and the deformation of the Marquette Range synclinorium.

Reference has been made above to the intrusive masses found within the Negaunee iron-formation. These intrusives are irregular in shape, but are often sill-like. They are best described as metadiabase rather than as diorite or greenstone, as used in earlier publications. Locally, the sills have been used as horizon markers in the absence of recognized primary differences in the Negaunee. It has been suggested that the age of these intrusives may be either Clarksburg or Keweenaw. Possibly they might be related to the Penokean orogeny. It has also been suggested that one or more of these sill-like masses is extrusive, but the bulk of the structural features indicate that they are intrusive. They reach a maximum thickness of some 700 feet. A general average would be of the order of 400 feet.

Various other intrusives are found cutting both the pre-Animikie and Animikie rocks. Some are fine-grained mafic and felsic dikes, others are medium to coarse-grained metapyroxenite and metagabbro. Some dikes are fresh diabases, both in composition and texture. Locally they may be inversely polarized magnetically.

Exposures of Jacobsville Cambrian sandstone are found south of Marquette. Typically, the Jacobsville is reddish, friable sandstone with some conglomerate and reddish shale. Some sandstones exposures are found, too, in the Gwinn District. Still further south is the onlap of the Ordovician rocks. Through all of the district, variable amounts of the recent Quaternary surficial material are found, principally of glacial origin.

The column in the Gwinn District (see Figure 4) has been compared to the principal synclinorium, and is summarized as follows from Allen (1914):

Paleozoic		Ordovician	Limestones and sandstone
Late		Cambrian	
Precambrian		Keweenaw	Intrusives
		Baraga	Princeton Series Ferruginous slate, cherty quartzite and graywacke conglomerate
	Middle	Menominee	Gwinn Series Dark gray slate, graywacke Iron-formation Dark gray to graphitic slate arkose and conglomerate
	Early		Granite, greenstone

Some geologist have considered the iron-formation in the Gwinn District as correlative to the Bijiki iron-formation in the Michigamme formation.

Metamorphic Zones

Studies have been made on the metamorphic zones in the Upper Peninsula. Particularly noteworthy is the study of James (1955). The area around Republic and the Republic Trough is shown on his maps to be of the highest intensity, in the sillimanite zone. The metamorphic intensity in the balance of the Marquette Iron Range decreases to the east. The Ishpeming-Negaunee extremity of the producing district is in the chlorite zone. The metamorphic isograds cross the geologic structures at high angles in many areas. This suggests that the metamorphism is post-structure.

Of considerable interest is the paper by James and Clayton (1962) relating mineral formation temperatures to their oxygen isotope fractionization. Some samples from the Marquette Range were tested, specifically from the Athens and Greenwood Mines and the Republic district. They tentatively conclude: (1) on the basis of internal consistency and consistent relations to the mineralogic evidence of metamorphic zoning, the isotopic data yields at least a fair approximation of temperatures of metamorphism through the garnet zones; (2) the temperature of metamorphism for the chlorite zone reaches approximately 200° C., that of the biotite zone approximately 275° C., and that of the garnet zone approximately 350°C.; (3) the rocks in the staurolite and sillimanite zones (upper part of the epidote amphibolite facies and amphibolite facies, respectively) were formed at temperatures above 350°C., and the present isotopic composition of the oxygen of these rocks is due to retrograde equilibration during temperature decline.

Nomenclature

From the time of the publication of Monograph 52 in 1911 until 1949 little change occurred in the petrographic nomenclature of the Marquette Mineral District. At that time, The Cleveland-Cliffs Iron Company undertook a sweeping revision of many of its rock names. Numerous old or ambiguous terms were replaced with modern or more precise terms. Various names had been used for the iron-formation in the past; at this time, the term "iron -formation" was adopted as the sole name. A uniform system of description was effected also.

The terms "hard ore jasper" and "soft ore jasper" previously used were eliminated. Our beneficiating plants at the Humboldt and Republic Mine are sometimes referred to in the press as processing "jasper" or "taconite"; however, the expression "iron-formation" is preferred.

Primary Iron-Formation

The summary of James (1954) on the Sedimentary Facies of Iron-Formation emphasized the four facies: carbonate, sulphide, silicate and oxide. Other references are Boyum-Anderson-Han (1955) Primary Features of the Negaunee Iron-Formation; and Anderson-Han (1956) The Relationship of Diagenesis, Metamorphism and Secondary Oxidation to the Concentrating Characteristics of the Negaunee Iron-Formation of the Marquette Range. The carbonate facies is thought to have been the principal primary constituent of the Negaunee iron-formation. Plate I-A illustrates an unoxidized remnant of typical cherty carbonate iron-formation. James (1954 pages 258 et seq.), advances arguments for the primary oxide facies (as hematite) in the upper part of the Negaunee iron-formation. The summary by Stone and Cumberlandidge (1964) on the Groveland Mine geology suggests that both hematite and magnetite were primary. Han (1962) has found some magnetite which he believes is primary oxide facies in several places in the Negaunee iron-formation. Specific illustrations of primary sulphides and silicates from the Marquette Range are not readily available.

Plate I-B illustrates the magnetitic chloritic clastic iron-formation found at the Empire Mine and the Tilden Mine in the southeast portion of the Marquette Range. Clastic iron-formation is also found on the Cascade Range. This suggests a source to the southeast of the synclinorium.

Alteration of the Iron-Formation

The principal alteration of the iron-formation has been by oxidation and enrichment under varying conditions. The average iron content of primary iron-formation approximates 26%, dried. The average altered Negaunee iron-formation approximates 31% Fe, dried. Locally in the Negaunee area, the average is higher, reaching about 35%. A general increase in porosity accompanies the alteration.

Where enrichment has occurred, it is most frequently characterized by replacement of the primary chert by iron oxides, primarily hematite and

goethite, and locally magnetite. The greater part of this alteration has been volume-for-volume replacement as very little slumping has been noted. In numerous instances it is possible to follow the primary bedding from the iron-formation into the ore. The ore contacts frequently cut the bedding at high angles.

The folding of the Marquette Range synclinorium was accompanied by the development of a strong joint system which increased the permeability of the iron-formation. Exploration and mining in recent years have indicated that both oxidation and enrichment extend to far greater depths than thought earlier. Numerous drill holes have cut rich ore grade material to depths of over 5,000 feet from the present land surface. The term "ore" is used here as meaning high iron content and does not necessarily imply an economic profit as the term is defined customarily. The deepest hole on the Range was drilled to a depth of 6,365 feet, NX (3 inch) size, and encountered oxidation and enrichment to the bottom. During late Precambrian time when the alteration may have occurred, the depth of this alteration was undoubtedly greater.

Some parts of the Negaunee contain considerable silicates such as sericite, grunerite-cummingtonite, hornblende and garnet in the higher metamorphic zones (such as at Humboldt and Republic); and minnesotaite, stilpnomelane and chlorite in the diagenetic or lower metamorphic zones (such as at Empire). According to one view, many or all of these silicates are derived by the metamorphism of earlier primary silicates. Others believe that these silicates are the result of the reaction of earlier iron minerals (carbonate and/or oxides) and the silica of the chert under metamorphic conditions. Plate I-C shows the development of the silicates. Plate I-D is a polished slab of magnetite carbonate silicate iron-formation. Plates I-E and F are photomicrographs of the slab showing the portions rich and lean in magnetite.

Ore Occurrences

There are four general types of ore which have been produced and shipped from the Marquette Iron Range. They are:

- High grade direct shipping "soft" ores,
- High grade direct shipping "hard" ores,
- Siliceous ores,
- Concentrates and agglomerates (pellets) from low grade iron-formations.

Traditionally in the Lake Superior Region, the direct shipping ores have a base iron content of 51.5% natural (moisture included). Recently, the direct

shipping ores have averaged 54% Fe, natural, reflecting the competition of the foreign ores. A premium is paid for the hard lump ores which have a size range of +2 inch -8 inch. Their average iron content is 61.5%. The siliceous type of ore, a specialty grade, constitutes small shipments of richer iron-formation which averages 38% Fe. The pellets range from 61 to 65% Fe, natural.

For many years the miners have made a distinction between "soft" ores and "hard" ores. In general, the soft ores are porous, friable, earthy to semi-plastic and are made up chiefly of hematite, and martite (locally still magnetite) and with minor amounts of goethite, unreplaced chert, and locally silicates (mica, chlorite) (see Plate III - M through P). The other extreme are the hard ores which are hard, dense, compact, with low porosity. The iron minerals are magnetite, martite, dense compact hematite, and specularite (see Plate III - Q through T). These ores form the lump product. A substantial amount of high grade ore mined would fall somewhere in between these two end types. Terms such as "semi-hard" have been used. Locally in the soft orebodies, substantial tonnages of "hard" ores have been found which are similar in macroscopic appearance to the hard ores of the hard ore mines, as shown in Plate III.

Soft Ores

Seventy per cent of the total production of the Marquette Iron Range, including the Cascade and Gwinn Districts, has been of the high grade direct shipping type of soft ore. The ores occurred, for the most part, in the basal portion of the Negaunee iron-formation. These deposits may be as thick as 260 feet, normal to the bedding, and have considerable lateral extent. The orebodies are generally found in the synclines and in fault structures bounded by basic dikes along at least one side. Figure 6 is a north-south section looking west passing through the eastern side of the City of Negaunee showing a variety of ore occurrences in this vicinity.

Locally the soft ores are found in "ore pipes" which are chimneys of ore extending some distance vertically, cutting the stratification of the iron-formation. In general, these ore pipes are 200 to 300 feet across and are localized at the intersection of two or more dikes cutting the iron-formation. This type of ore has been characterized also by its low phosphorus content and by "heavy ground."

The other major type of soft ore occurs on the large intrusive sills near the upper part of the iron-formation. These soft ores were some of the first to be exploited in the Ishpeming area. The ore is of irregular distribution both as to its occurrence and its thickness. The principal locality in which these orebodies were found is to the south of Ishpeming toward the axis of the

Marquette Range synclinorium. We do not have any mines operating in this type of ore occurrence at this time, although around the turn of the century this was an important ore source. It is interesting to note that these soft ores, lying on the metadiabase sheets, are limited by the same structural controls as the ore lying on the footwall contact. In general, the ores were high in iron content and low in phosphorus and sulphur.

A sizable tonnage of soft ore in Negaunee is impregnated with gypsum. Sulfur analyses range from 0.2 to over 3.0%. The gypsiferous ores occur at definite elevations (near the present sea level) cutting across the bedding of the iron-formation.

Hard Ores

The hard ores amount to 20% of the total production to date. Most of them are found in the uppermost portion of the Negaunee iron-formation and immediately below the Goodrich formation contact. The ores were made up of hard, compact to specular hematite, and magnetite (see Plate III). Accessory minerals may include garnet and tourmaline. The footwall of the ore may be unoxidized iron-formation, oxidized iron-formation of the "jaspilite" type, or one of the intrusive sills. The hanging wall may consist of material of the Goodrich formation, oxidized iron-formation or -less commonly - intrusive material. The orebodies are frequently related to intrusive dikes. Replacement features are noted in the hard ores as well as in the soft ores. The outlines of hard orebodies are frequently related to structural features such as folds, faults and dikes. Some hard ores are also found locally near the base of the Negaunee iron-formation, as a part of the soft orebodies.

The basal Goodrich material consists of conglomerates, argillites, slates and quartzites. Locally a conglomerate may contain a sufficient amount of ore, either in the form of pebbles or the matrix material, to be merchantable for mining. The intrusives which cut the hard ore are quite frequently confused with the argillite of the Goodrich. Both materials are fine-grained and highly altered, making identification difficult.

Presently there are two active hard ore properties in the Range: the Cliffs Shaft and the Champion Mines. Former major hard ore properties, now inactive, include the Lake Superior Hard Ore, Humboldt, Republic, Michigamme and Greenwood Mines. The Cliffs Shaft Mine structure is a westerly plunging syncline, having a cross-fold under the town of Ishpeming. The Greenwood and Champion Mines, by contrast, are located on the south limb of the synclinorium. These hard orebodies have a definite westward plunge and extend some distance below the present land surface. At Republic Mine the ores were mined some 4,000 feet along the plunge, or 2,800 feet vertically.

Concnetrating Ores

The first of the modern beneficiating properties in Michigan was the Humboldt Mine. This property has been producing high grade concentrates since 1954, and pellets since 1960. The crude ore consists of the specularitic magnetic cherty iron-formation at the top of the Negaunee. Concentration is by froth flotation. The Republic Mine is similar, having started production of pellets in 1956. Plates II-K and L illustrate the specularitic and specularitic magnetitic iron-formations which are the crude ores. Both Humboldt and Republic Mines were formerly producers of high grade ores.

The Empire Mine is mining a magnetitic carbonate silicate cherty iron-formation in the lower section of the Negaunee iron-formation. Concentration is by magnetic separation. Plates I-D, E and F, and Plates II-G, H, I, and J illustrate some of this crude ore.

Genesis of the High Grade Ores

There has been no universal agreement on the origin of the high grade ores of the Marquette Iron Range. There are difference in opinion, also, regarding both the method and the timing of the enrichment of the hard ores as opposed to the soft ores. The soft ores are discussed first.

Soft Ores

Certain features are common to most hypotheses of the origin of the soft ores:

1. Fracturing of the iron-formation was important in permitting access for water to oxidize the primary iron-formation, to remove silica and to transport the iron which replaced much of the silica.
2. The silica was removed presumably by the same solutions that carried the iron. Inasmuch as no remnants of the removed silica have been identified on the Marquette Range, it is assumed that it was carried to the ancient surface.
3. The orebodies are found only in the Negaunee and Bijiki iron-formations. Other rock types in the column may have been altered and enriched locally, but no significant tonnage of high grade soft ore has been found in any of the other geologic numbers.
4. The soft orebodies are found lying on the Siamo footwall and on the metadiabase sheets in "trough-like" or "open-facing" structures. These less

permeable members may be folded and/or faulted, but appear to act as "bottom" surfaces.

5. The major structural controls of folding, faulting and most intrusives were pre-ore. Some intrusives are post-ore and, according to some observers, some faulting and possibly some of the folding are post-ore.

6. Few of the deeper major orebodies extend to ledge surface up the dip or up the pitch, but the oxidation of the iron-formation adjacent to the orebodies definitely does extend to ledge.

7. Any hypotheses must account for the circulation of a hydraulic system which extends to depths of over 6,000 feet from present surface.

8. Most soft ores contain varying amounts of clay mineral assemblages that indicate temperatures higher than normal ground-water temperatures. The relations of these clay minerals to the iron minerals is not conclusive. They are not established as definitely contemporaneous.

Cold Water Origin

Monograph 28 reviewed the various ideas of soft ore origin and advanced the basic cold water hypothesis. The agent of oxidation, solution of silica, and introduction of iron was oxygen-bearing ground-waters. The iron which replaced the silica was derived from other portions of the iron-formation. In 1935, C. K. Leith et al (pages 24-26), modified the hypothesis by proposing that the chemical activity of the circulating ground-waters had been increased by heating due to Keweenaw lavas and intrusives. They also observed that oxidation is found at greater depth than would be expected of normal ground-water circulation even under mountainous conditions.

Hydrothermal Origin

In 1926, J. W. Gruner proposed a hydrothermal origin for Vermilion Iron Range ores. In 1929 he extended this hypothesis to the formation of high grade ores throughout the Lake Superior region. Gruner's hypothesis stressed the greater dissolving power of hot water on silica. The thermal conditions would stimulate hydraulic circulation. Objections were raised to the idea that these waters were juvenile on the basis that most of the Lake Superior intrusives were basic and therefore relatively "dry". In 1937, he published his "modified theory" which proposes that the ore-forming fluids were principally meteoric waters which had been heated by igneous emanations. He conceded also that not all of the introduced iron came from these emanations. Gruner explained the observed differences in resultant ore types as being related to differences in primary iron-formation, structural conditions, temperatures of the water, and relative quantities of emanations.

Summary on Soft Ore Genesis

The theories of Leith and Gruner are not too dissimilar. Aside from Gruner's "emanations," the ore-forming process is almost the same, the differences being only a matter of degree. The geometry of the soft orebodies is significant in stressing the complicated "plumbing" of the hydraulic systems. Many of the orebodies are found on the "open" side of structural traps. Some have no apparent relationship to the present surface.

The mineralogy may be significant also. Recent microscopic work by Tsu-Ming Han has found appreciable martite in the soft ores, as shown in Plate III. O and P. The semi-hard ores found in the soft orebodies are essentially made up of equigranular martite, some of which contains traces to appreciable magnetite remnants. Han suggests that the martitization was contemporaneous with the soft ore formation.

Lastly, as pointed out above, some of the clay minerals suggest temperature higher than those of normal ground-waters. The writer noted dickite and chrome nontronite in the Marquette Range ores in 1945, as described by Gruner (1946). The paper by Bailey and Tyler (1960) describes dickite, kaolinite (non-definitive), nacrite, talc, pyrophyllite, 1M and 2M₁ muscovite, lizardite, clinochrysotile, Al-serpentine, dioctahedral and trioctahedral chlorite, dioctahedral and trioctahedral montmorillonite, palygorskite, and regular interstratifications of chlorite-montmorillonite, as well as the non-clay minerals apatite, alunite, gypsum, clacite, and rhodochrosite. Bailey and Tyler state on pages 155 and 156, "In summary, both the synthesis data and the evidence provided by field relationships for similar clays elsewhere in the world suggest that the clay mineral assemblage in the Michigan iron ores is primarily the result of hydrothermal activity. . . . The intimate association of the clay minerals with the iron ore suggests that these differences may also extend to the origin of the ore itself."

As noted earlier, the soft ores are found in the chlorite zone of metamorphism.

Hard Ores

The hard ores are more complex than the soft ores. There may be two or more modes of origin and times of formation. Significant features are:

1. The hard ores are found in the upper 200 feet of the Negaunee iron-formation. Most commonly, the hard ore is at the Goodrich contact.
2. The hard ores are in "closed" structures, such as anticlinal flexures, under less permeable rocks.

3. Commonly, the iron-formation adjacent to the ore is the "oxide-facies" - jaspilite, the reddish, pinkish banded chert the miners once called "hard ore jasper."

4. Hard ores tend to have equigranular iron minerals, little to no porosity, few vugs and no botryoidal textures.

5. The magnetite ores are commonly in discontinuous masses in specularitic iron-formation and ore. The chert associated with magnetite ore is gray rather than reddish. In some areas magnetite orebodies and magnetitic iron-formation are traversed by quartz veins containing tourmaline, very coarse specularite and crystalline siderite with minor pyrite, sphalerite and chalcopyrite.

6. Frequently the hard ores extend down into the iron-formation as "droppers," appearing to have been formed by replacing the iron-formation.

7. Locally, at the Goodrich contact, some massive hard ore contains detrital quartz which suggests that the original iron minerals may have had a similar detrital origin.

8. Above the hard ores and at the base of the Goodrich, one finds conglomerates of varying thickness. The conglomerate may contain much detrital chert or quartz, and some ore fragments that appear to have been ore at the time of deposition.

9. Dynamic metamorphism has been responsible for the formation of the specular hematite in the ores and adjacent iron-formation.

10. No hard ore is found in the Bijiki iron-formation.

Hypotheses of Hard Ore Origin

Monograph 52, pages 278-279, outlines a possible origin and time sequence of ore formation. The upper portion of the Negaunee iron-formation was exposed to weathering and concentration (mechanical classification?) to produce an iron rich product. Burial by the Goodrich and later formations followed. After the deposition of the Michigamme formation, the Animikie sediments were folded, faulted and intruded. The metamorphism associated with the structural deformation formed the hard ores from the weathered ores.

Post-Keweenawan erosion re-exposed the Negaunee and Bijiki iron-formations. They were altered by ground-waters to form the soft ores, as outlined earlier. Since the soft ores were formed after the dynamic metamorphism, they do not display the specular hematite and other features of the hard ore.

The objection to this concept centers on the "weathered-surface" origin for all of the hard ores. It is necessary to postulate some introduction of iron to explain both the geometry and detailed features of many hard orebodies. This introduction of iron must have been accomplished before or during metamorphism.

The hydrothermal school of thought would ascribe much of the hard ores to replacement of the iron-formation by high temperature solutions.

An Alternate Time Sequence

The continuing research each year by the mining companies, and the current mapping by the U. S. Geological Survey, add materially to our information on the geology of the Marquette Range. More age-dating will be done to help establish time-sequences of ore-formation. The writer believes that a better understanding of the relationship of the metadiabases, the Clarksburg pyroclastics and the Penokean orogeny will alter the classic time-sequence. This will help us understand the effects of Keweenawan vulcanism.

Other Ores of Economic Interest

Numerous gold, silver and lead prospects have been noted north of Ishpeming in the Pre-Animikie series. The age of the mineralization is thought to be post-middle Animikie by T. M. Broderick (1945) who described the major gold occurrence at the Ropes Gold Mine. A total of \$703,000 was recovered from this operation during the period of 1883 to 1897.

Significant amounts of uranium oxide have been detected in the iron-formation on the Marquette Range and in the Gwinn District. Thorium-rich monazite has been noted in the Goodrich quartzite and conglomerate of the Cascade District, as described by Vickers (1956).

Acknowledgment

Grateful acknowledgment is made to the writer's colleagues in The Cleveland-Cliffs Iron Company, Inland Steel Company and Jones and Laughlin Steel Corporation, and their managements, for assistance in preparing this summary. The writer particularly appreciates the cooperation and contributions by the U. S. Geological Survey and the Michigan Geological Survey. Special

thanks are due to Dr. Jacob Gair.

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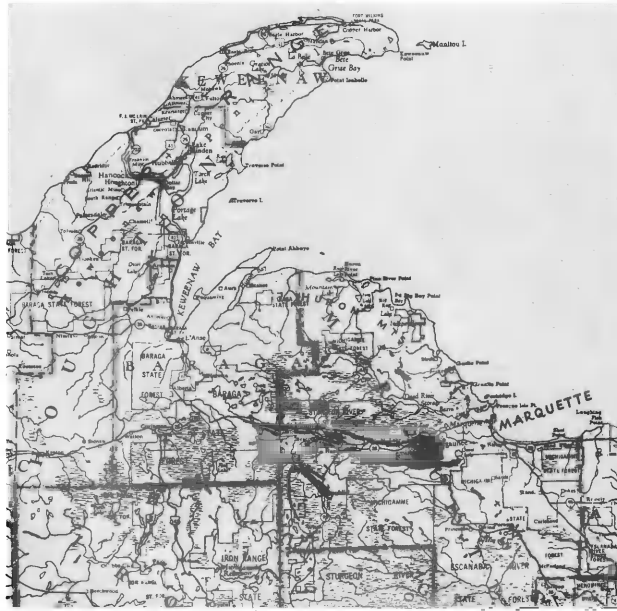


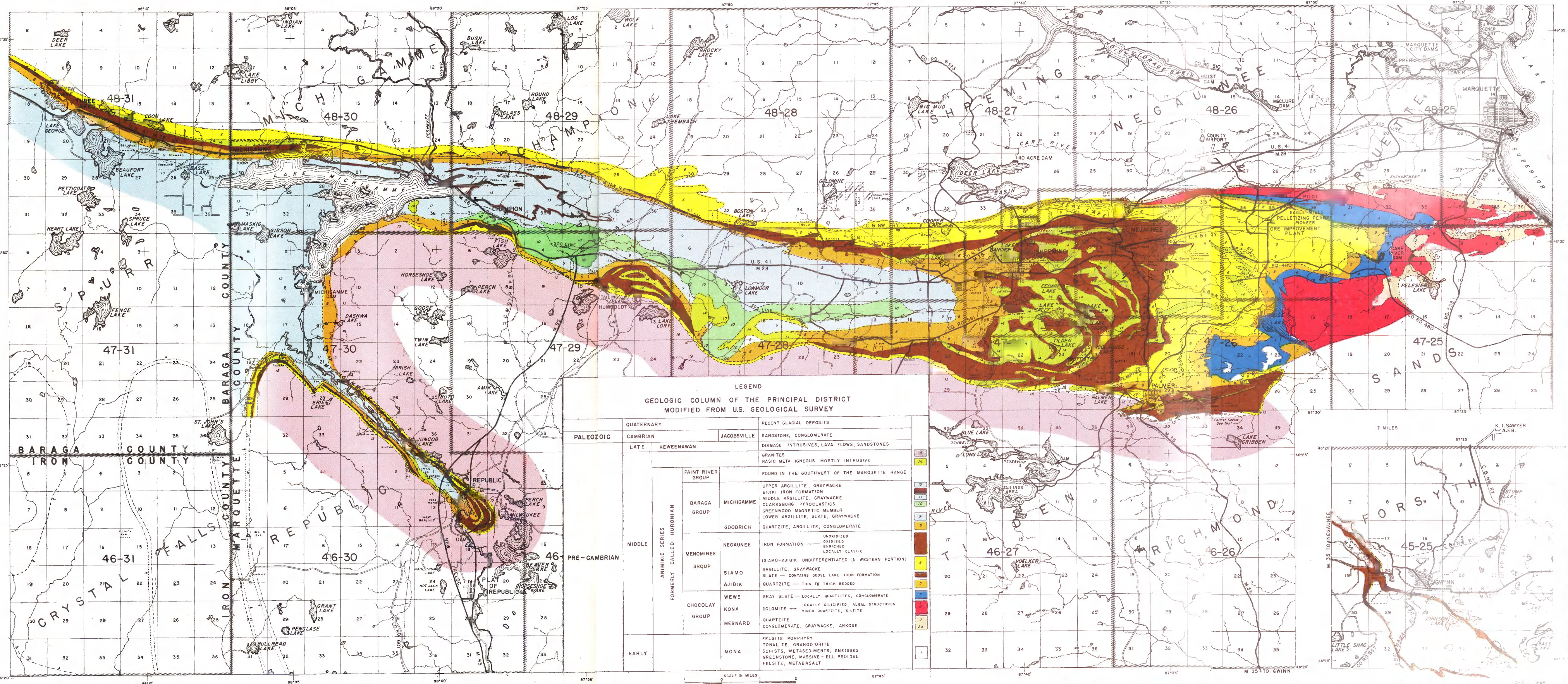
Figure 1 - Location Map of Marquette Mineral District
(Base from Aero Service Corp.)



Figure 3 - Underground Sub-Level Stopping



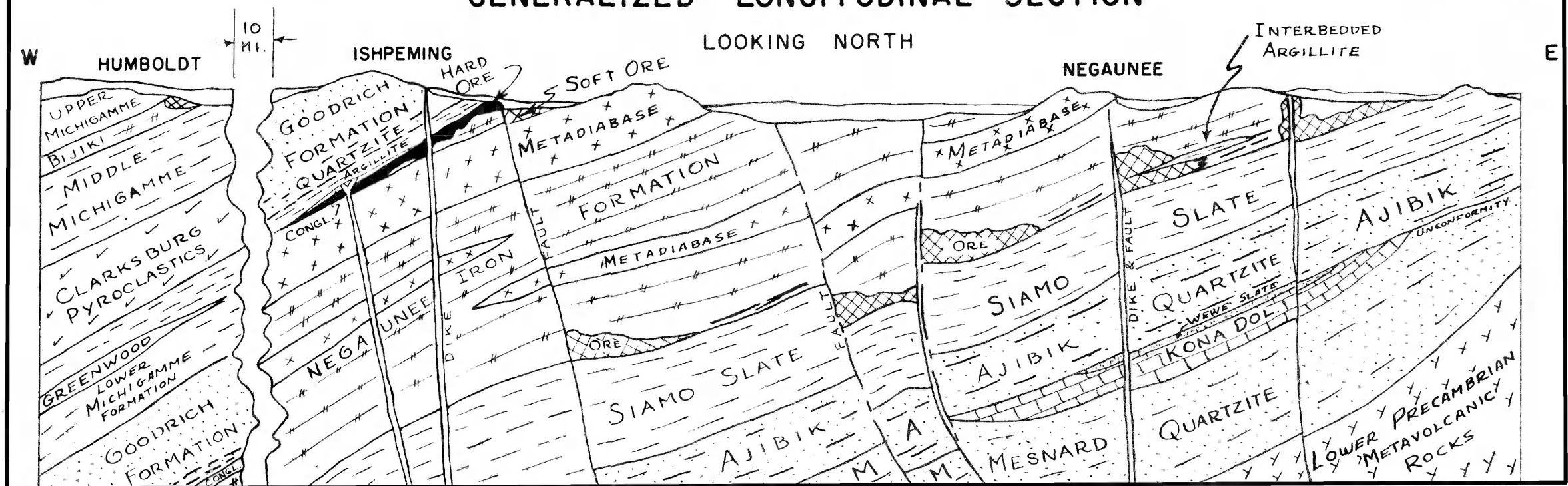
Figure 2 - North Jackson Mine No. 1 Pit, 1860



MARQUETTE IRON RANGE - MICHIGAN

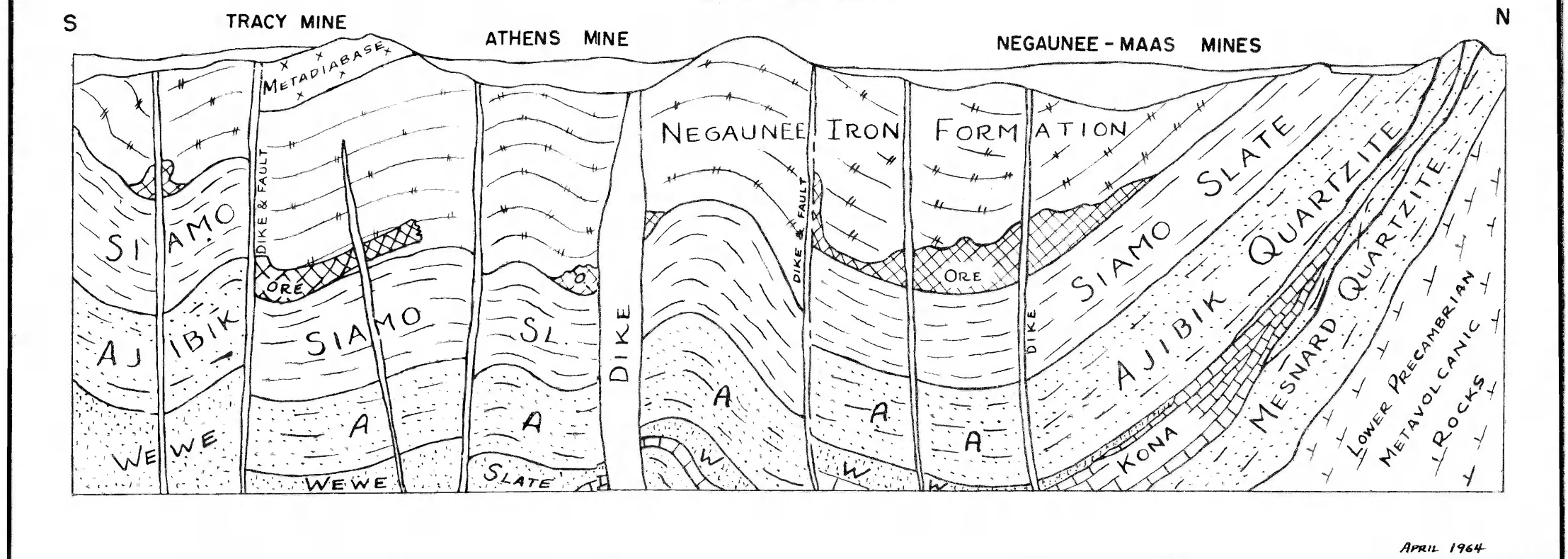
GENERALIZED LONGITUDINAL SECTION

FIGURE 5



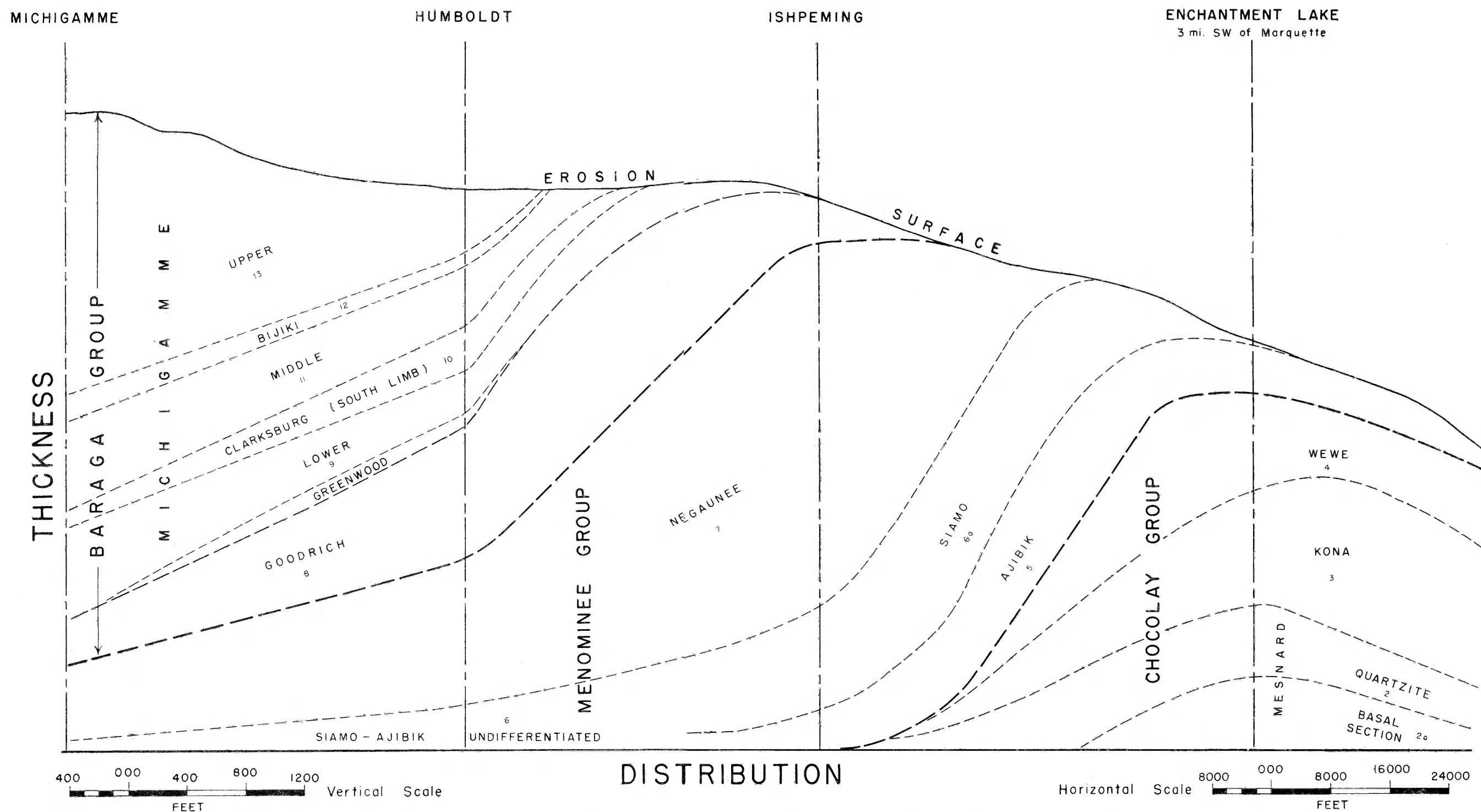
GENERALIZED N-S CROSS SECTION ONE MILE EAST OF WEST LINE OF R.26W LOOKING WEST

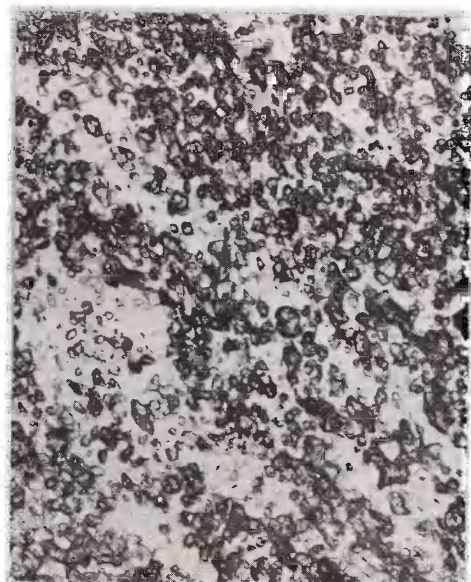
FIGURE 6



APRIL 1964

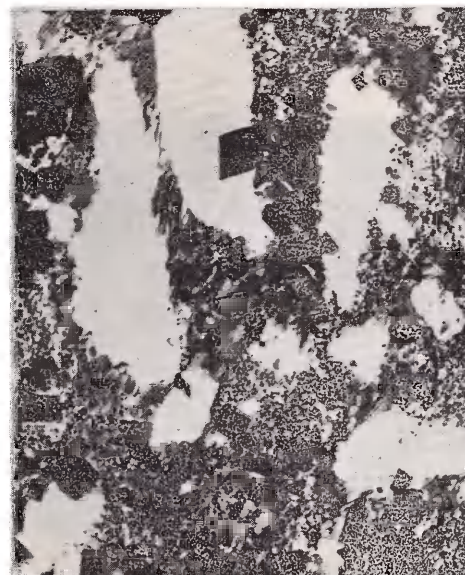
GRAPH SHOWING RELATIVE THICKNESSES OF ANIMIKIE SEDIMENTS ON THE MARQUETTE RANGE LOOKING NORTH



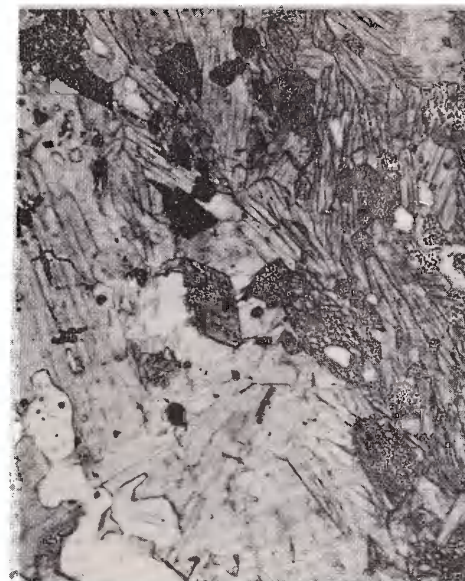


A. Cherty Carbonate I-Fm.
Thin section 200X Athens Mine
Magnesium iron carbonate
granules, various shades;
chert, white

Magnetite lamina alternating
with silicate-carbonate
Silicate-carbonate
Silicate-chert containing
some carbonate
Magnetite lamina alternating
with magnetite-chert-
carbonate-silicate
Chert-silicate containing
carbonate and magnetite
Magnetite lamina alternating
with magnetite-chert-
carbonate-silicate



B. Mag. Chloritic Clastic I-Fm.
Thin section 100X Empire Mine
Coarse magnetite and quartz
granules with chloritic
groundmass



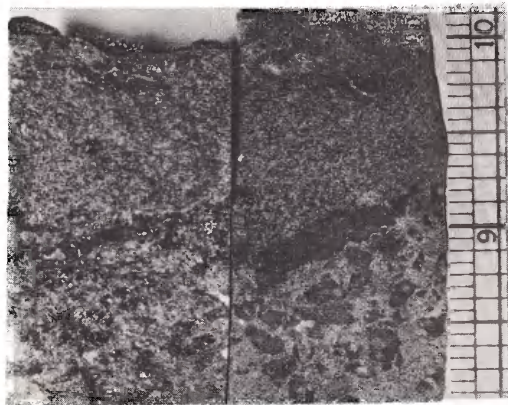
C. Mag. Grunetic Cherty I-Fm.
Thin section 100X Republic Mine
Grunetic, gray; chert, dusty
white; magnetite, black



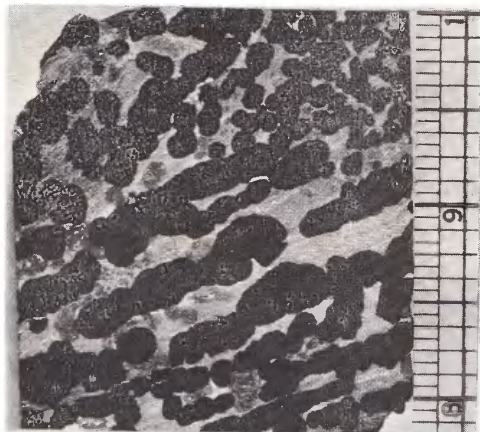
D. Polished slab of Iron-Formation
Natural scale

E. and F. Pol.Sec. 100X

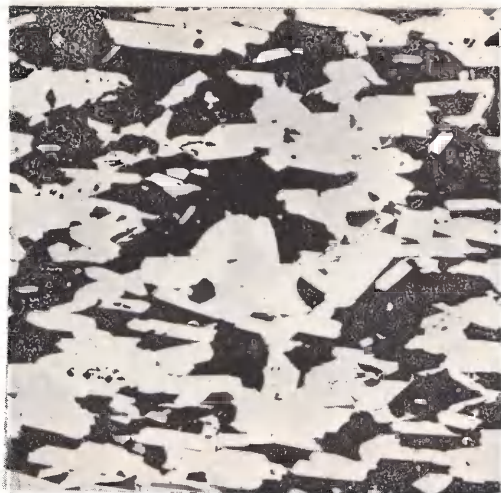
Plate II - Photomicrographs



G. Martitic Cherty Clastic I-Fm. Natural size



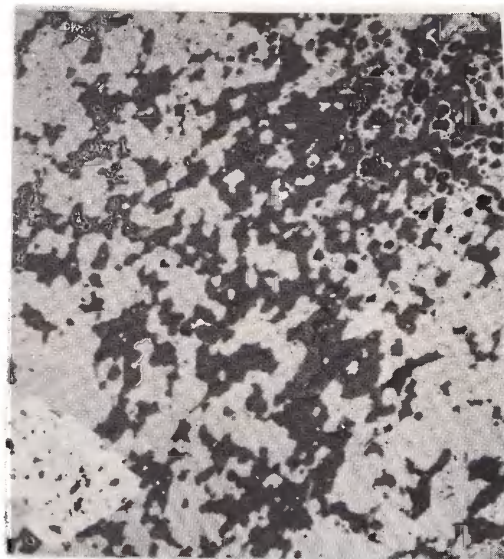
I. Cherty Goethitic I-Fm. Natural size



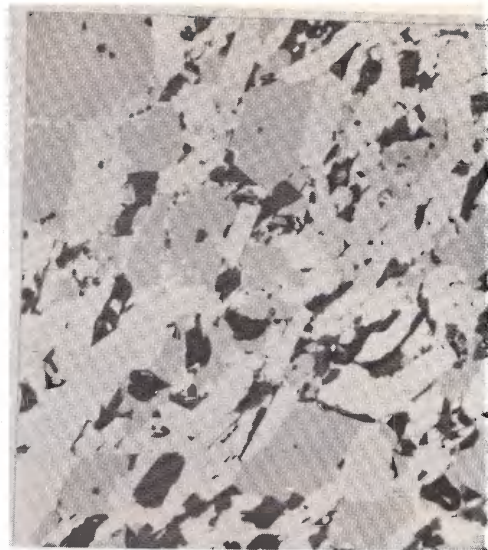
K. Specularitic Cherty I-Fm. Pol. Sec. 100X - Hematite, white; chert, black



H. Same - Pol. Sec. 100X Martite, white; magnetite, whitish gray; chert and quartz, dark gray

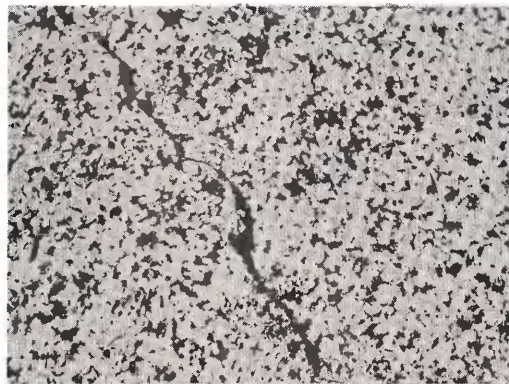


J. Same - Pol. Sec. 100X Martite, white; goethite, gray; chert, dark gray; and pits, black

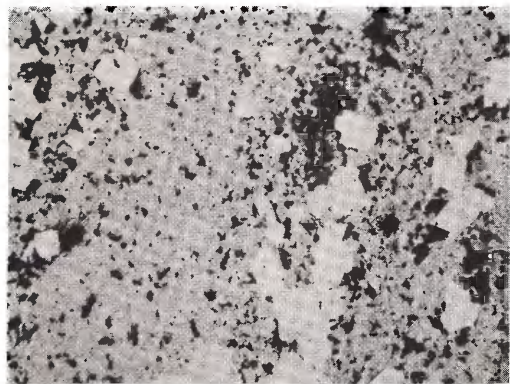


L. Magnetic Specularitic Cherty I-Fm. Pol. Sec. 100X Hematite, white; magnetite, gray; chert, dark gray

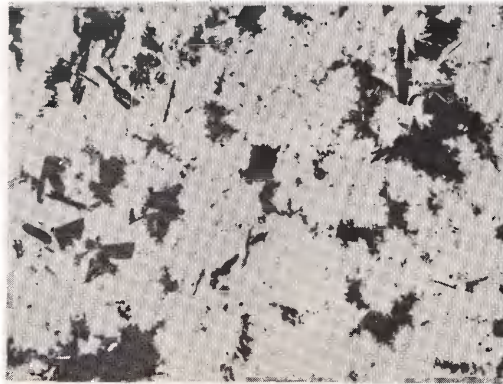
Plate III - Photomicrographs



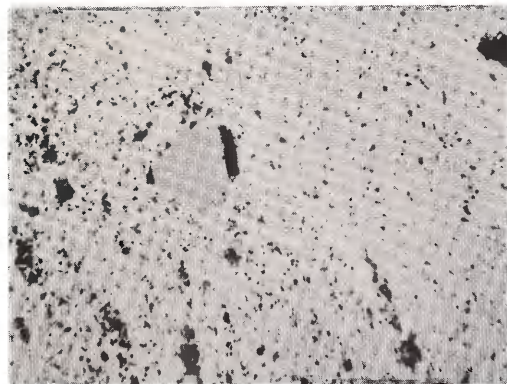
M. Mather soft hematite.
Hematite white.
Pol. sec. 100x.



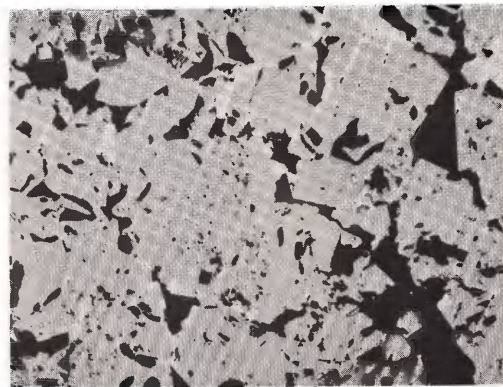
O. Mather soft martitic ore.
Martite, white, chert,
dark.
Hematite, greyish white.
Pol. sec. 100x



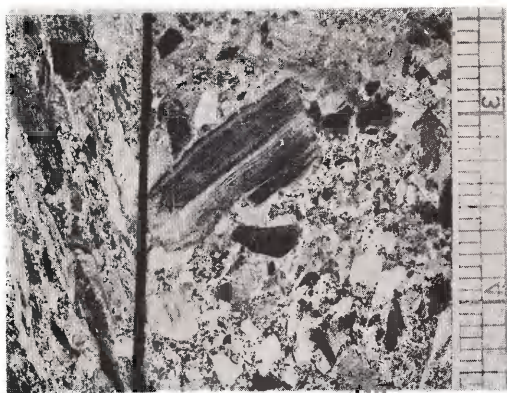
As M. 500x
Hematite, white; and
gangue and pores, dark
grey.



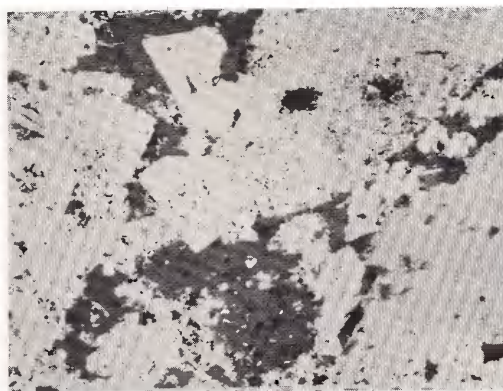
Q. Cliffs-Shaft hard hematite S.
Hematite, white; and
Magnetite, greyish white.
Pol. sec. 100x



R. Cliffs-Shaft Magnetite.
Magnetite, greyish white;
hematite, white; gangue,
dark grey, and pit black.
Pol. sec. 100x



S. Cliffs-Shaft ore
conglomerate.
Natural size.

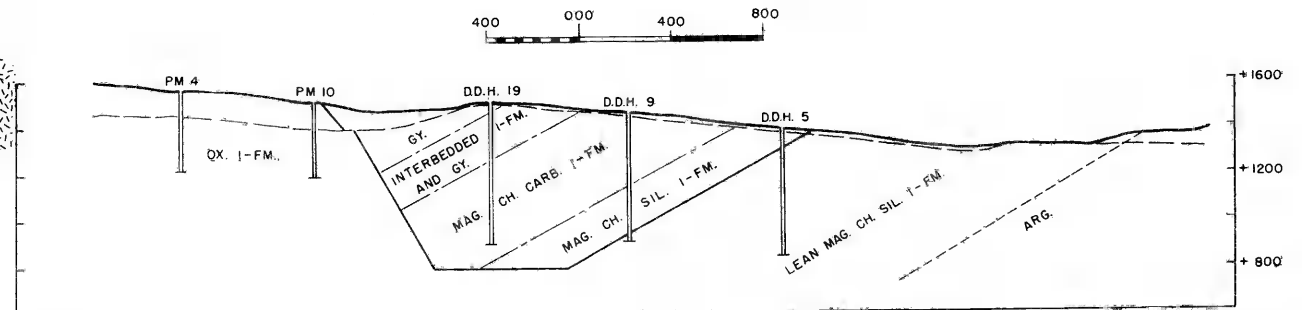


T. As S. Pol. sec. 100x
Hematite, greyish
white; martite, white;
gangue, dark grey.

GEOLOGY OF NEGAUNEE IRON FORMATION EMPIRE MINE AREA AND CASCADE DISTRICT

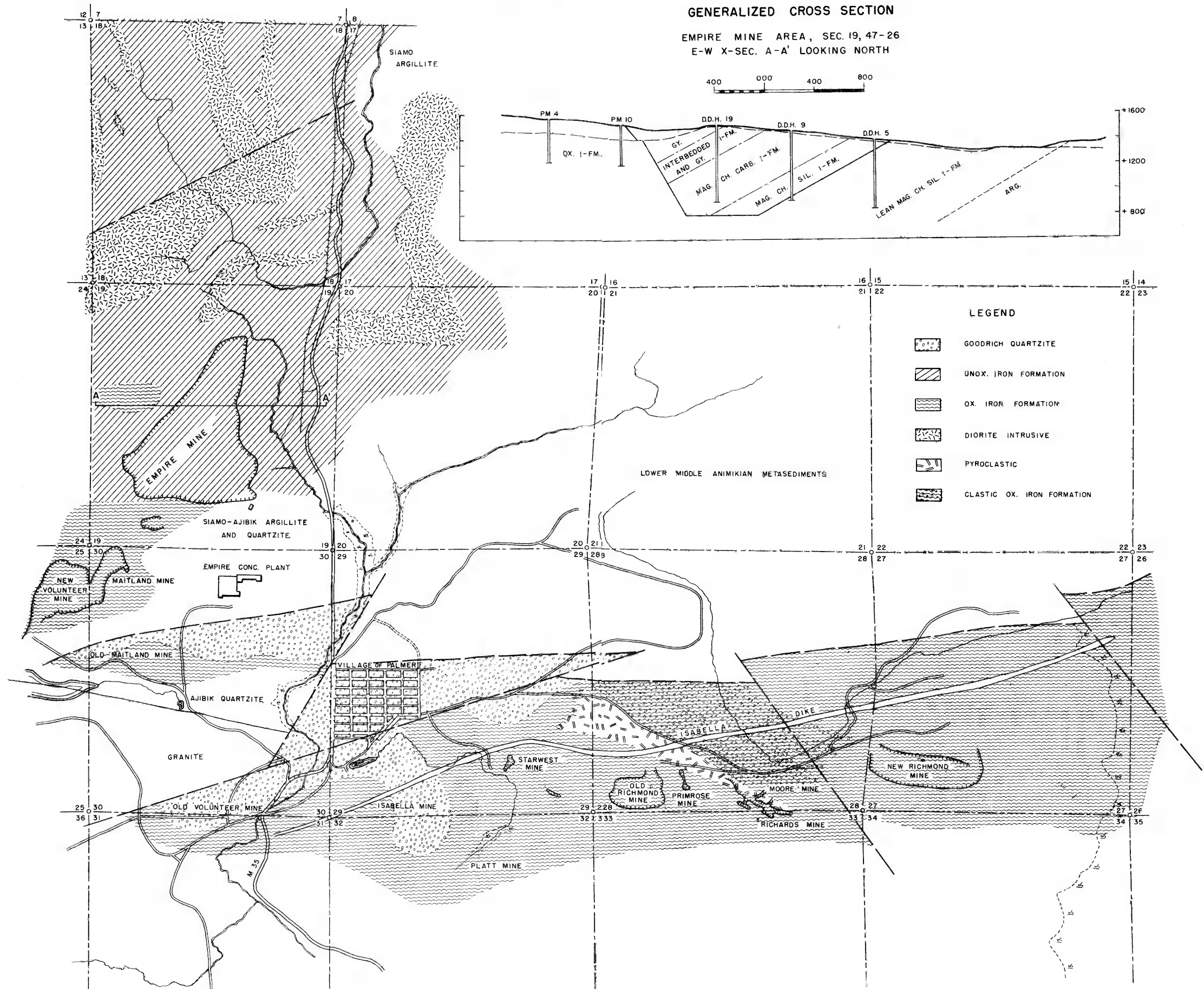


GENERALIZED CROSS SECTION
EMPIRE MINE AREA, SEC. 19, 47-26
E-W X-SEC. A-A' LOOKING NORTH

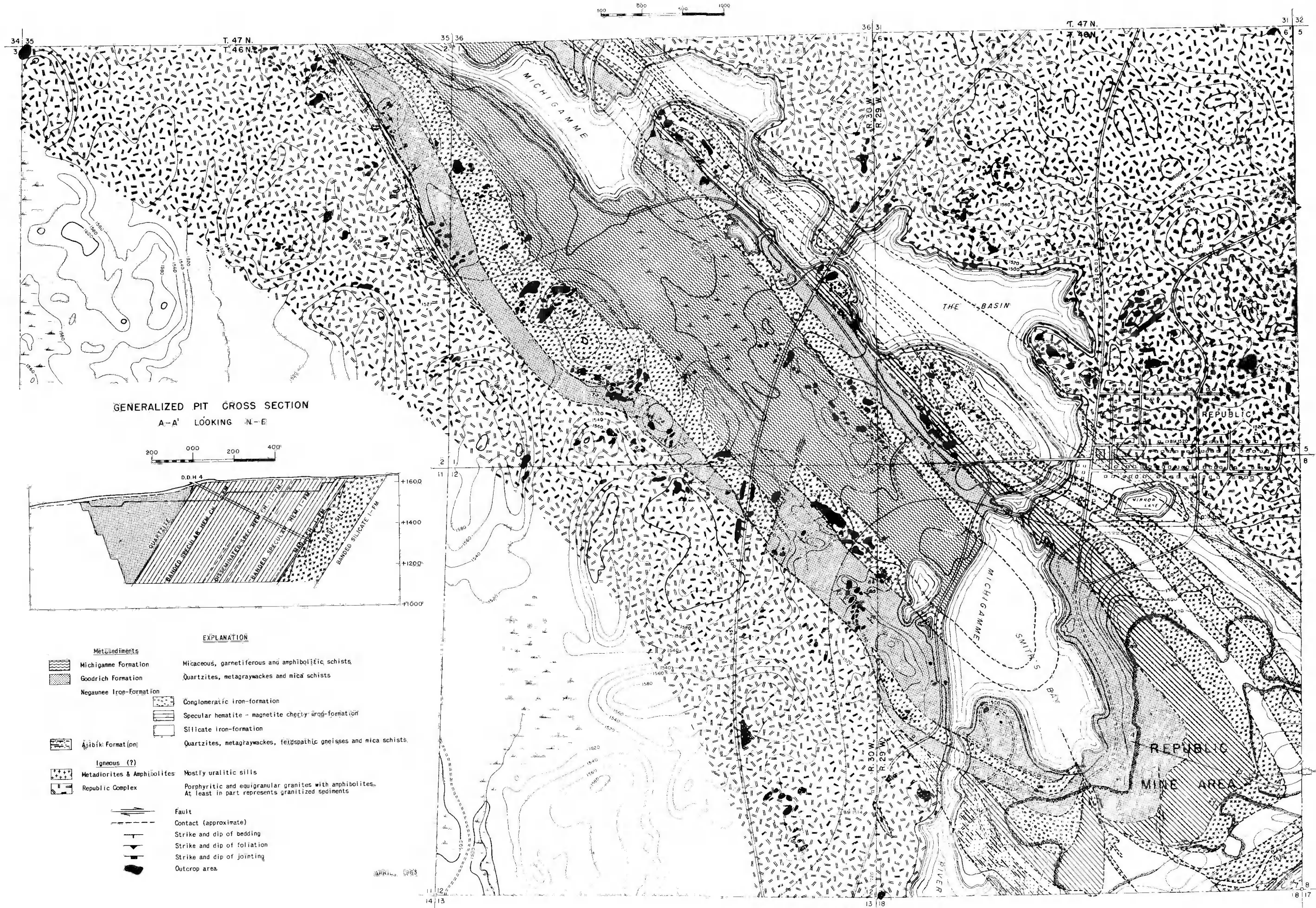


LEGEND

- GOODRICH QUARTZITE
- UNOX. IRON FORMATION
- OX. IRON FORMATION
- DIORITE INTRUSIVE
- PYROCLASTIC
- CLASTIC OX. IRON FORMATION



GEOLOGY OF THE REPUBLIC MINE AREA



Department of the Interior
United States Geological Survey*

FIELD TRIP

MARQUETTE IRON-MINING DISTRICT AND REPUBLIC TROUGH

by

Jacob E. Gair, U. S. Geological Survey

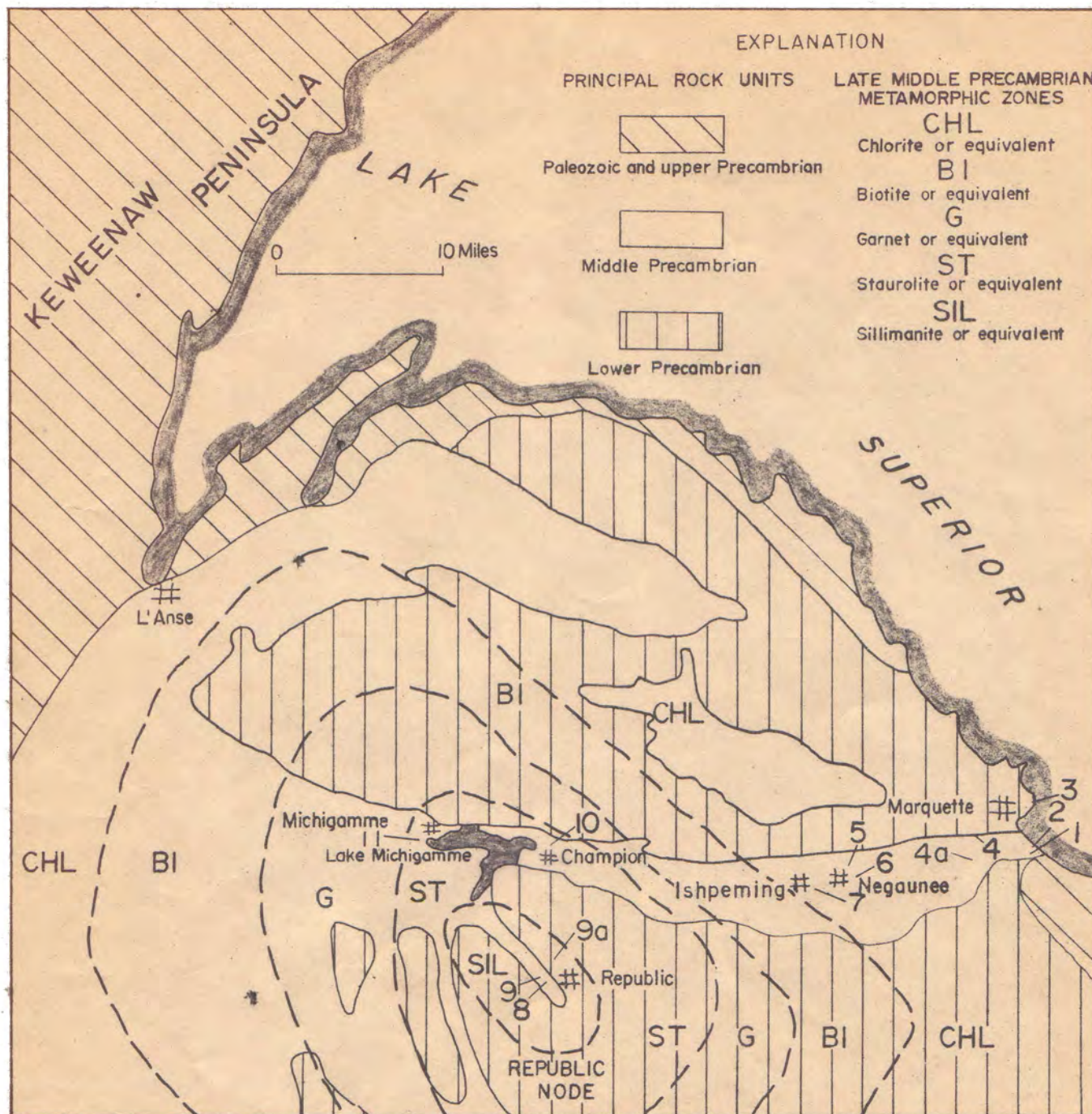
Conducted in conjunction with the

TENTH ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY

Ishpeming, Michigan, May 9, 1964

Supplement to B. H. Boyum's District Guidebook.

*This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.



MAP OF METAMORPHIC ZONES

(Late Middle Precambrian metamorphism)

Marquette Iron-Mining District, Republic Trough, and vicinity

Numbers show approximate locations of field trip stops.

Map modified from H.L. James, Zones of Regional Metamorphism in the Precambrian of Northern Michigan, Bull., Geol. Soc. America, V.66, 1955, plate I. Metamorphic zones are as shown by James.

ITINERARY

<u>Stop</u>		<u>Page</u>
1.	U. S. Hwy. 41, Harvey Quarry. Mona Schist, Mesnard Quartzite and Kona Dolomite.	1 & 2
2.	Shore outcrop, Lake Superior, southeast of entrance to Marquette State Prison. Mesnard Quartzite and Jacobsville Sandstone.	2
3.	Lighthouse Point. Layered Mona Schist cut by metafelsite, metadiabase, and diabase.	3 & 4
4.	Enchantment Lake section. Mesnard Quartzite and Mona Schist.	4 & 5
4a.	South bank of Carp River. Conglomerate at base of Ajibik Quartzite, and Wewe Slate. (If time is running short, this stop will be omitted.)	5
Lunch and Rest at Negaunee Township Community Building		
5.	U. S. Hwy. 41, northeast edge of Negaunee. Siamo Slate.	6 & 7
6.	R.R. cut north of Athens mine headframe. Carbonate-facies of Negaunee Iron-Formation.	7
7.	Jasper Knob, Ishpeming, Quartz-hematite (jaspilite) facies of Negaunee Iron Formation.	8
8.	Kloman Mine property, Republic, Magnetite-grunerite-quartz and hematite-quartz facies of Negaunee Iron-Formation.	8 & 9
9.	First outcrop south of Michigamme River bridge on Michigan Hwy. 95, west of Republic. Garnetiferous Michigamme Slate in core of Republic trough.	9 & 10
9a.	Michigan Hwy. 95, 2 miles N. of Republic. Lower Precambrian gneiss cut by amphibolitic and biotitic dikes. (If time is running short, this stop will be omitted).	10 & 11
Rest.	Junction Michigan Hwy. 95 and U.S. Hwy. 41.	
10.	Champion. Layered gruneritic Bijiki Iron-Formation.	11
11.	2 miles southwest of Michigamme. Staurolite schist in Michigamme Slate.	11 & 12

GEOLOGY AT FIELD TRIP LOCALITIES

Stop 1.

Road cut on U. S. Hwy. 41, and Harvey Quarry, approximately 3 miles southeast of Marquette. See Map A. Letters in parentheses below refer to locations on map.

From near the northwest end of the large road cut on U. S. Hwy. 41 (a), the group will proceed southeastward to the end of the road cut, from there along the base of the east-facing slope into the Harvey Quarry, and thence southward along the base of the quarry face.

This locality represents the easternmost exposure of lower and middle Precambrian rocks in the Marquette district, except for a small island of Mesnard Quartzite in Lake Superior about 1/2 mile northeast of here.

Mesnard Quartzite is overlain with apparent conformity by Kona Dolomite and is in fault contact with basement greenschist (Mona Schist). Because of a north-south crossfold about 3/4 mile to the west, the Mesnard and Kona here occupy an eastward-plunging syncline, in contrast to the normally westward-plunging folds in the eastern part of the Marquette synclinorium. Whether this eastward-plunging syncline is merely the western part of a local canoe-shaped fold, or whether it represents a major and regional reversal of plung is unknown.

At the roadside, 400 feet northwest of the northwest end of the large road cut (a) is an exposure of white-weathering vitreous Mesnard Quartzite. Rusty iron stains are common. The quartzite strikes a little north of east and dips steeply southward, beneath and in apparent conformity with Kona slate in the road cut to the southeast.

The northwest half of the large road cut (a) exposes mainly thinly laminated green, pink, and maroon slates in the lower part of the Kona. These rocks dip steeply southward with some undulation, and are strongly cleaved. Cleavage-bedding relationships indicate that these rocks lie north of a synclinal axis and cleavage-bedding intersections plunge eastward. Thin layers of reddish or maroon quartzite and dolomite, up to 4 feet thick, are interbedded in the slate. Pods of vein quartz are common in parts of the slate and in general are aligned with the rock cleavage. Southeastward and stratigraphically upward in the road cut, dolomite beds become more common in the slate and a thick bed of reddish brown ferruginous dolomitic quartzite (b) is exposed between 60 and 150 feet from the southeast end of the road cut. At the southeast end (c) a trail leads westward uphill about 50 feet to a cliff in which can be seen large domed algal structures in Kona Dolomite. At the base of the slope almost directly below the algal structures, gentle folds in dolomite plunge about 35° E. (d). From this place southward, bedding dips to the north and cleavage-bedding relationships indicate that the synclinal axis lies to the north. The axis of the east-plunging syncline therefore passes through the exposure of algal structures. The slate in the Kona on the south limb of the syncline is only about half as thick as on the north limb. This difference is attributed to faulting on the south limb.

Stop 1. -- continued

Near the north end of the Harvey Quarry (e) a dike of metadiabase cuts at a low angle across the Kona-Mesnard contact. Just south of the dike several narrow shear zones cut the Mesnard Quartzite. Across most of the northern half of the Harvey Quarry (f), Mesnard Quartzite dips 30° - 50° N. About midway along its length, the quarry narrows and just north of that place (g) Mesnard Quartzite is in fault contact with Mona Schist--a greenish chlorite-sericite-quartz schist. Adjacent to the fault the Mesnard has been dragged into steep northward dips, it is badly fractured, and is cut by vein quartz. Faulted segments of sericite slate indicate that the lower part of the Mesnard was involved in the faulting. Apparently most of the lower Mesnard has been faulted out.

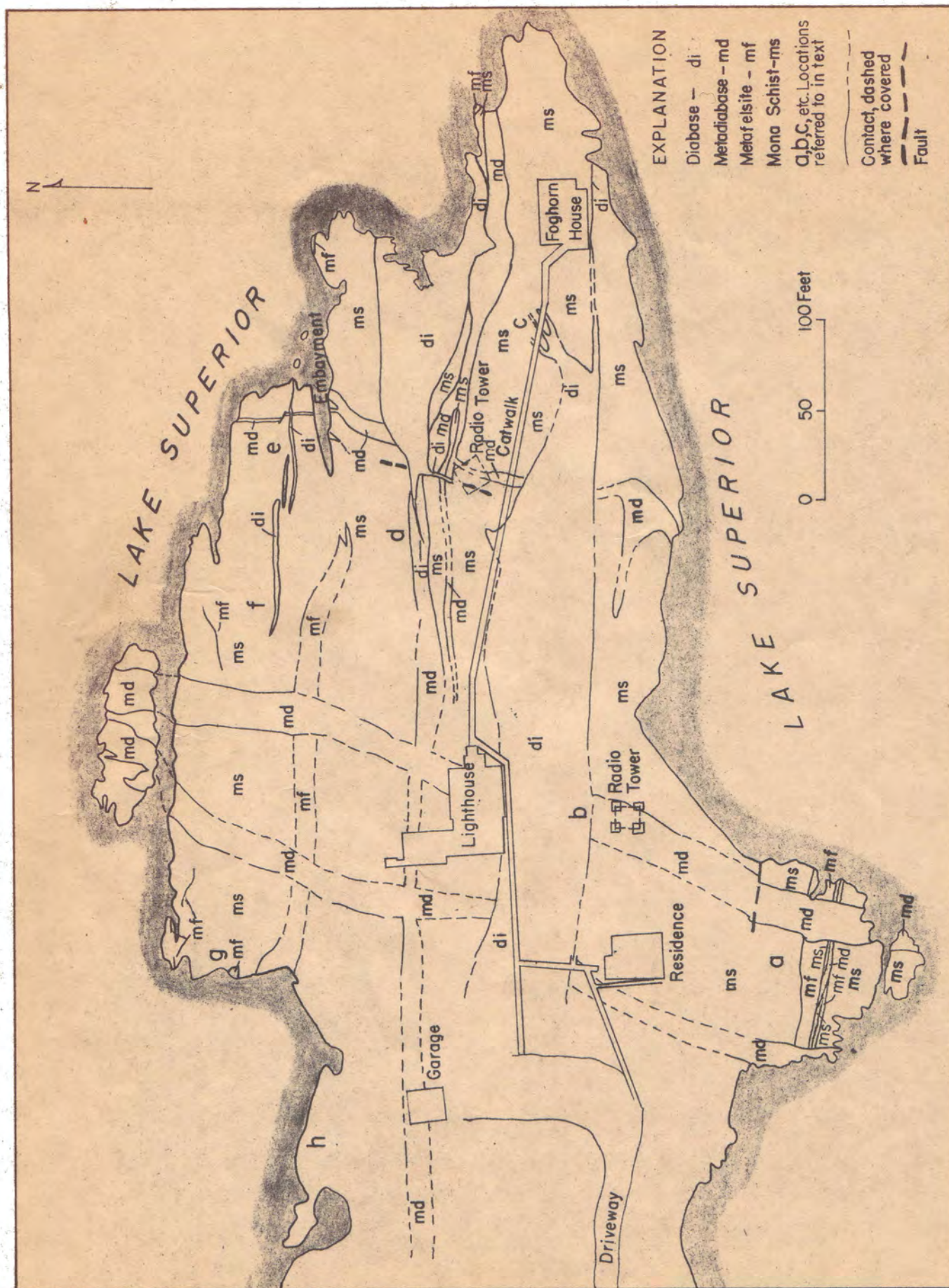
South of the Mesnard-Mona contact (g) in the Harvey Quarry several different varieties of Mona Schist are exposed (h). Thin felsic dikes as much as 10 inches thick, thin quartz veins, and metadiabase dikes cut the Mona. Mineral assemblages in the Mona are rich in chlorite or tremolite-actinolite and indicate low-grade regional metamorphism in the chlorite zone (or the greenschist facies). The felsic dikes are interpreted as offshoots of gneiss exposed 1/2 mile to the west, and constitute supporting evidence that the gneiss is younger than the Mona Schist.

Stop 2.

Outcrop on shore of Lake Superior, east of U. S. Hwy. 41 and railroad tracks, 2000 feet southeast of entrance to Marquette State Prison. Companion outcrop on southwest side of highway. See Map A.

At this place, vertically dipping Mesnard Quartzite of early middle Precambrian age, located on the north limb of the Marquette synclinorium, is unconformably overlain by gently dipping Jacobsville Sandstone of Cambrian age.

White-weathering vitreous Mesnard Quartzite in beds 4-8 inches thick strikes eastward and dips 80° S. to vertically. Crossbeds and ripple marks indicate top directions to the south in conformance with the position of the quartzite on the north limb of the synclinorium. Reddish Jacobsville Sandstone dips $10-15^{\circ}$ eastward to southeastward and is in visible contact with the Mesnard. Remnant patches of Jacobsville are "plastered" against the north side of the quartzite outcrop, and on the south side of the quartzite, the Mesnard-Jacobsville contact is steep. Evidently during deposition of the Jacobsville, the Mesnard at this place formed a small topographic rib much as it does now. Flat-lying Jacobsville occurs on the flank of Mt. Mesnard, some 3/4 mile west and 370 feet above this shore locality, which indicates a Cambrian topographic relief and ruggedness approximating or greater than that adjacent to the present shore of Lake Superior.



Modified from planetable map by J.E. Gair and R.E. Thoden, U.S. Geological Survey, 1959.

MAP B - Sketch map showing geology at Lighthouse Point, Marquette, Michigan

Stop 3.

Lighthouse Point, Marquette

From the parking area, proceed eastward along south side of point, cross catwalk a short distance west of foghorn house and return along north side of point. See Map B. Letters in parentheses below refer to locations on map.

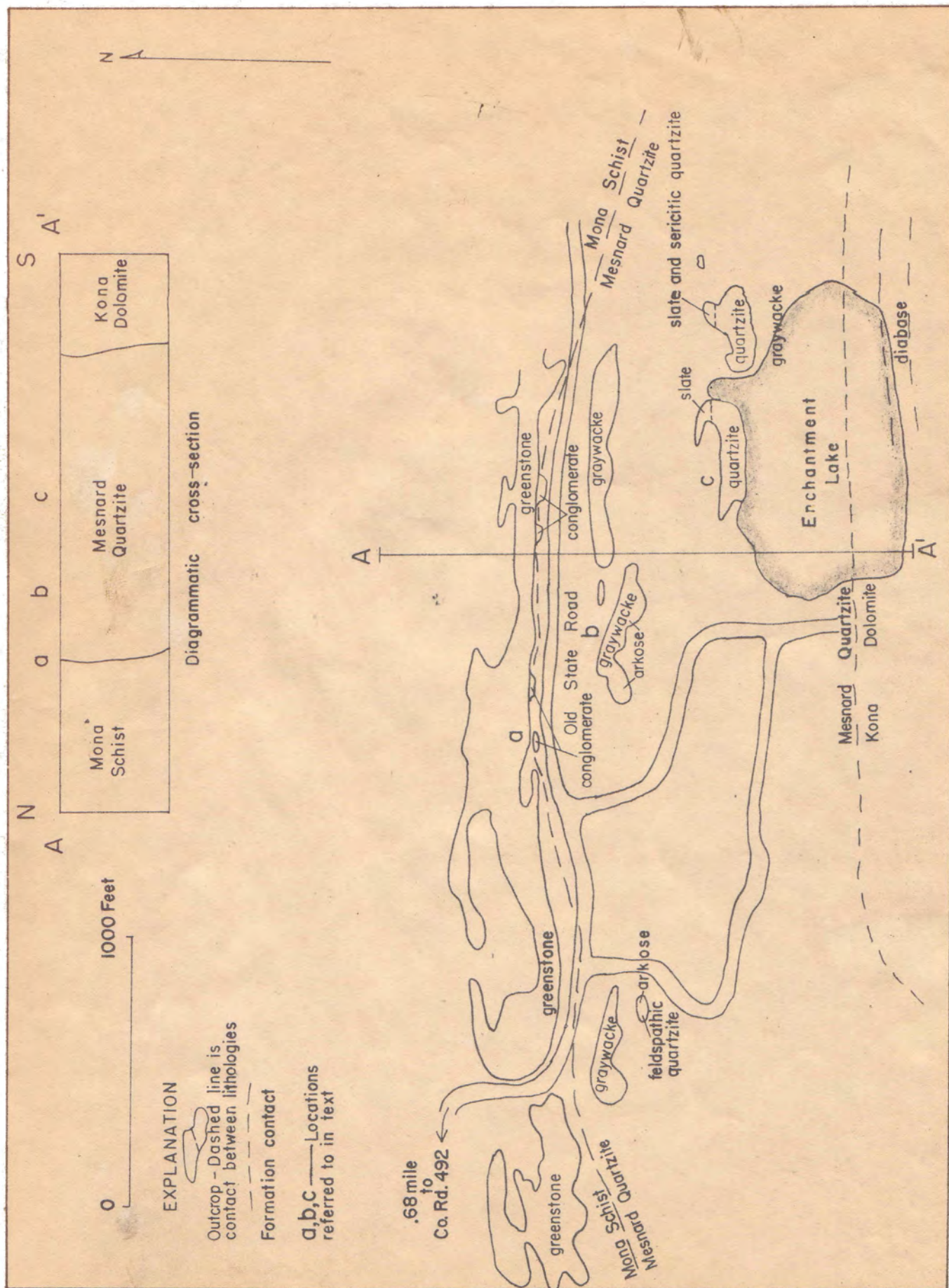
At this locality lower Precambrian layered and massive amphibolitic schists are cut by intrusive metafelsite, metadiabase, and diabase. The schists comprise the upper part of the Mena Schist and are interpreted as metamorphosed mafic tuff with some interlayered mafic flow rock. The ages of the metafelsite and metadiabase are not known closely. The metafelsite may be an offshoot of the lower Precambrian gneiss, but the evidence is tenuous, and the metadiabase may be either of early or middle Precambrian age. The diabase is of late Precambrian (Keweenaw) age. The last regional metamorphism in the area, which occurred at the end of middle Precambrian time, establishes a limit on the youngest possible age of the metamorphosed rocks and provides a basis for recognizing that the nonmetamorphosed diabase is post-middle Precambrian in age.

The spatial relationships of layered schist, metafelsite, and metadiabase are clearly seen on the small south-jutting point (a), 200 feet southwest of the lighthouse. A sill-like body of metafelsite, about 10 feet thick, and a much thinner adjacent layer occur in the layered amphibolitic schist. Both the metafelsite and the schist are truncated by two north-northeast-trending dikes of metadiabase, one on the west side and one near the east side of the south-jutting point.

Immediately north of the radio tower, some 50 feet south of the lighthouse (b), the eastern of the two north-trending metadiabase dikes can be seen to be truncated by a westward-trending diabase sill. The sill is about 50 feet thick here and extends westward for many miles, but it pinches out 300 feet east of here (c) near the foghorn house. North of where it pinches out another diabase sill, about 60 feet thick, extends onto Lighthouse Point from the east, intrudes a sill of metadiabase and pinches out about 150 feet (d) from the east end of the point.

On the northeast side of the point (e), north of the narrow east-west embayment, a thin north-trending dike of metadiabase is crossed by a thin west-trending dike of diabase that gently crosscuts the amphibolitic host rock. To the west (f), the steeply north-dipping layers of schist are well exposed. West of location (f) along the north side of Lighthouse Point, the two north-northeast-trending metadiabase dikes observed on the south side are again seen, and several sills or gently crosscutting dikes of metafelsite, an inch or two thick, can be seen in the schist.

At the west edge of the exposure (g) a wedge of metafelsite truncates the layered schist. Along the north beach just west of the main area of exposure there is an outcrop of mixed layered and massive amphibolitic schist (h), which is interpreted as having originated as interlayered tuff and flow rock.



MAP C - Sketch map and diagrammatic cross-section, A-A', showing geology at Stop 4 near Enchantment Lake

Stop 3. -- continued

Typical mineral assemblages in the amphibolitic schist consist mainly of blue-green hornblende and oligoclase-andesine. The metamorphic grade of these rocks is higher than that of the crosscutting mafic dikes and of the lower part of the Mona Schist to the south. The higher grade mineral assemblages here are believed to be relict from early Precambrian metamorphism related to the intrusion of the gneiss.

Stop 4.

Enchantment Lake Section, approximately 4 miles southwest of Marquette (south-central part of sec. 29, T. 49 N., R. 25 W.-- formerly Mud Lake or Old State Road locality). See Map C. Letters in parentheses below refer to locations on map.

After examining outcrops 50 to 150 feet north of the Old State Road (a), look at exposures 200-300 feet south of the road (b) and proceed southeastward to the hill (c) overlooking the north side of Enchantment Lake. From there return northward to the Old State Road and along the road westward to the starting point.

This is a classic locality described by C. R. Van Hise and W. R. Bayley in U. S. Geological Survey Monograph 28 on the geology of the Marquette iron-bearing district (1897). Here can be seen the lowermost part of the middle Precambrian section along the north limb of the Marquette synclinorium, in vertical contact with lower Precambrian slaty greenstone on the north.

Immediately north of the Old State Road (a) there are several exposures of basal conglomerate of the Mesnard, containing fragments of tonalitic gneiss and greenstone. The matrix is rich in chlorite. The conglomerate can be seen in sharp vertical contact with slaty greenstone of the Mona Schist. Within 100 feet north of the contact the Mona Schist becomes comparatively massive. Near the contact both the greenstone and the conglomerate are strongly foliated and steeply plunging to vertical lineations are common on foliation surfaces.

Fine-grained slaty graywacke overlies the conglomerate but is not seen in contact with it. The graywacke is exposed in elongate outcrops (b) occurring along the north side and top of a low westward-trending ridge south of the Old State Road. Bedding has not been definitely recognized, but the rock has a strong foliation (cleavage) which strikes parallel to the trend of the formation and dips approximately parallel to the basal contact of the conglomerate to the north.

Fine-grained salmon-colored arkose is exposed along the south side of the westward-trending ridge, stratigraphically above the graywacke. Small scattered exposures along the top of the ridge suggest some interbedding of graywacke and arkose.

Stop 4. - continued

Fissile olive-green sericite slate, which is stratigraphically above the graywacke and arkose, is exposed on the north slope of the hill (c) lying immediately north of Enchantment Lake. Near the north brow of the hill, the slate contains thin seams of clastic quartz and appears to grade southward into quartzite within a few feet. Southward across the top of the hill to the cliff at the north edge of the lake, vertically dipping white-weathering vitreous Mesnard Quartzite stratigraphically above the sericite slate, is well exposed.

The conglomerate-graywacke-arkose-slate sequence below the white vitreous part of the Mesnard is similar to and is correlated with the Fern Creek Formation, which occurs below Sturgeon Quartzite on the Menominee Range.

Saussuritic mineral assemblages in Mona Schist north of the Old State Road and chlorite-sericite-quartz assemblages in the fine-grained graywacke south of the road indicate metamorphism in the chlorite zone or the lower part of the greenschist facies.

Stop 4a.

Exposure along south side of Carp River, 900 feet west of Carp River bridge, SE 1/4 sec. 6, T. 47 N., R. 25 W., approximately 5 miles southwest of Marquette

This is one of several localities in the area where conglomerate is exposed at the base of the Ajibik Quartzite, indicating that Ajibik deposition was preceded by an erosional interval. This locality is in the trough area of the Marquette synclinorium, and has middle Precambrian formations striking generally northward as they cross the main axis of the synclinorium. Ajibik Quartzite rests on Wewe Slate in a long narrow outcrop immediately south of the alder swamp bordering the south bank of the Carp River. There is some variation in strike from northwestward to northward along the outcrop, but near the contact between Ajibik and Wewe, the formations strike northward and dip 15° - 20° W., with no apparent angular discordance between them within the limits of the exposure. The Wewe, exposed near the east end of the outcrop, is a dark-gray argillaceous rock. It is overlain by 40 to 50 feet of thin-bedded Ajibik Quartzite, which in turn is overlain by approximately 50 feet of massive thick-bedded quartzite. The base of the Ajibik is marked by a bed of conglomerate, 1 to 2 feet thick, in which there are angular and subrounded fragments of argillaceous slate, chert, and quartzose rock.

Directly to the north across the Carp River and on strike with the Ajibik and Wewe of the south bank, Siamo Slate strikes northeastward and dips 35° - 75° NW. A west-northwestward-trending fault is inferred between these formations, following approximately along the river bed.

Stop 5.

Road cut on southeast side of U.S. 41, near northeast edge of Negaunee, NW 1/4 SE 1/4 sec. 31, T. 48 N., R. 26 W., and companion outcrop on the northwest side of highway, near historic marker at edge of Beverly Hills Park.

Data pertaining to orientation and thicknesses of bedding in the following description are based on observations by C. E. Fritts, U. S. Geological Survey.

Typical Siamo Slate is exposed here on the north limb of the Marquette synclinorium, about 450 to 600 feet above the Ajibik Quartzite and roughly 1100 feet below the Negaunee Iron-Formation. It is a pelitic rock containing quartz, chlorite, and sericite. The fresh rock is dark to light gray or gray green. The slate tends to weather to gray brown or pale yellow brown. Beds that contain some sideritic (?) carbonate weather reddish brown.

Bedding strikes generally westward and dips 50° - 60° S., but its orientation varies locally on drag folds. This is well shown in the low outcrop on the northwest side of the highway. A very characteristic feature of the Siamo, which is prominently displayed in the road cut, is the interbedding of slate of pelitic composition and coarser grained clastic rock that is generally lighter gray or gray green than the slate. This clastic rock contains varying amounts of clastic quartz and feldspar and argillaceous matrix minerals. Most is feldspathic quartzite or arkose, but graywacke, sericitic quartzite, and a graywacke-like rock with a carbonate-muscovite matrix also occur in the exposure. At both the southwest end and near the northeast end of the road cut, 20 to 25 feet of arkosic rocks occur in beds 1 to 5 feet thick. Interbedded in the slate that is exposed between these thicker zones of arkosic rocks are thin graywacke or other clastic beds, 1 to 6 inches thick. On the south side of the road cut exposure tightly folded slate is in contact with thick monoclinal dipping arkosic rock.

Note that the prominent cleavage cutting the slate layers in the central part of the road cut dips southward more steeply than the bedding. The cleavage-bedding relationships indicate that a synclinal axis lies to the south and are thus consistent with the location of the exposure on the north limb of the synclinorium. The cleavage evidently is a product of the major deformation that occurred at the end of middle Precambrian time.

Lenses of graywacke or sericitic quartzite that transect the bedding of the slate are a peculiar feature at this locality. It cannot be stated with certainty whether these are clastic dikes or faulted segments of normal beds. Undoubted clastic dikes that cut Siamo Slate a few miles southeast of Negaunee have no consistent orientation, but bend irregularly as they cross the slate. In the road cut, on the other hand, the rather consistent parallelism and near parallelism of the clastic lenses with cleavage in the slate suggest that the lenses are segments of beds that were broken and differentially shoved into the slate along or close to surfaces of shearing during the late middle Precambrian deformation. Somewhat similar differential slippage is indicated along the contact between the tightly folded slate and monoclinal dipping arkosic rock on the south side of the exposure.

Stop 5. -- continued

Quartz-chlorite-sericite assemblages in the Siamo are characteristic of pelitic rocks in the chlorite zone or the lower part of the greenschist facies of regional metamorphism. The Siamo Slate here therefore is of low metamorphic grade.

NOTE: Description and discussion for Stops 6-11 were prepared in collaboration with H. L. James.

Stop 6.

Railroad cut north of Athens Mine headframe and Marquette County Hwy. 480, in eastern part of City of Negaunee.

Rock typical of the lower part of the Negaunee Iron-Formation is exposed in the railroad cut. Sills of greenstone (metadiabase) less than 1 foot thick can be seen in the iron-formation along the south side of the tracks. The exposure shows a typical example of the carbonate-facies of iron-formation.

The iron-formation here consists mainly of alternating laminae of sideritic carbonate and fine-grained quartz (chert), but some layers contain as much as 15 percent minnesotaite, which imparts a greenish color, and some contain a small amount of magnetite. Laminae characteristically range from paper thin to about half a centimeter in thickness. Layers are not pure; the quartzose layers in particular tend to have crystals of carbonate scattered through them. In the fresh rock the darker gray-green laminae are the richer in carbonate and minnesotaite. Note the fine grain size, which is characteristic of the iron-formation in the low-grade (chlorite) metamorphic zone here in the eastern part of the Marquette synclinorium.

This exposure provides striking examples of the effects of surface weathering, oxidation, and replacement on sideritic iron-formation. The weathering-oxidation effects have taken place within a relatively few years since the present railroad cut was made. Oxidation-replacement has advanced inward from cracks and exposed surfaces, first causing the conversion of layers richer in carbonate into yellow-brown to reddish-brown goethitic iron oxide, and eventually changing quartzose laminae into iron oxide, too, as witnessed by the continuous zones of rusty iron oxide replacing both sideritic and quartzose laminae within a few millimeters of access surfaces. These surficial effects are rudely analogous to those that occurred in carbonate-facies iron-formation during the growth of bodies of soft earthy hematite in synclines and other "upward-facing" structural settings. The replacement of quartz (chert) by iron oxide, such as seen in the Athens railroad cut, occurs more readily and extensively in finer grained iron-formation than in coarser grained iron-formation. This relationship has been an important factor contributing to the greater development of soft earthy iron ore in the eastern part of the Marquette district than in the western part, where owing to higher grades of metamorphism, quartz grains are as much as 50 times larger than in the eastern part of the district.

Stop 7.

Jasper Knob, Ishpeming
NW1/4 sec. 11, T. 47 N., R. 27 W.

Classic exposures of the jaspilitic upper part of the Negaunee Iron-Formation may be seen on Jasper Knob. These exposures lie in the central part of the Marquette synclinorium, north of the major fold axis of the district.

The iron-formation characteristically has alternating thin beds and lenses of steel-gray, dark-blue-gray, dark-gray, or black specular hematite and bright-red hematitic fine-grained cherty quartzite. Beds commonly range in thickness from a fraction of a millimeter to about 2 centimeters, and fine internal laminations can be seen in the thicker layers. Specularite plates are strongly oriented parallel to bedding in the hematitic layers. Excellent colored illustrations of this rock have been published in U. S. Geological Survey Monograph 28.

Folds with drag folds on their limbs, and themselves comprising drag folds on the limb of a still larger fold, are strikingly displayed in most exposures. Fold axes are horizontal to gently plunging. In cross section the south limbs of individual anticlinal drag folds commonly are longer than the north limbs, indicating that the major synclinal axis passes south of Jasper Knob.

Small breccia zones ^{OCCUR} in the iron-formation at this locality. Along them, the comparatively brittle reddish cherty (jasper) layers in particular have been fragmented. Fractures have been healed mainly by crystalline hematite. Some of the breccia zones may correspond in orientation to axial plane cleavage.

Two principal theories have been advanced for the origin of the jaspilitic iron-formation at Jasper Knob. One theory advocates oxidation of a siderite-chert iron-formation during the post-Negaunee erosional interval and its recrystallization to specularite-quartz during the late middle Precambrian orogeny and metamorphism. This theory would account for patches of jaspilite in carbonate-facies iron-formation which are present near contacts between the two rocks, as for example in the Cliffs Shaft mine about 1/2 mile northwest of here. The second theory advocates a primary origin for the iron oxide, either as depositional hematite or as magnetite derived by diagenetic modification of depositional oxides. Physically, particularly in the very even bedding, the rock here resembles magnetite-rich facies of iron-formation rather than hematitic facies, which is characteristically irregularly bedded and oolitic.

Stop 8.

Kloman Mine Property

Outcrops north of section line road, 1/4 mile west of Republic and approximately 1,000 feet east, 50-100 feet north of southwest corner of sec. 6, T. 46 N., R. 29 W.

(See geologic map of the Republic Mine area in district guidebook by B. H. Boyum)

Stop 8. -- continued

These outcrops are part of a group extending northwestward from here that expose thin-layered Negaunee Iron-Formation on the northeast limb of the tight Republic syncline. The iron-formation strikes northwestward and dips vertically to steeply southwestward. The top direction in the middle Precambrian metasedimentary sequence here is to the southwest toward the axis of the syncline. The open pit of the Republic mine is 3,500 to 5,500 feet southeast of here on the nose of the syncline.

The productive upper part of the iron-formation in this area consists mostly of quartz-hematite jaspilite. Stratigraphically below the jaspilite is about 50 feet of magnetite-quartz iron-formation, and below that the lower half or so of the Negaunee is largely gruneritic iron-formation. This lower part of the iron-formation has been intruded by three mafic sills, now metamorphosed to amphibolite.

At Stop 8, magnetite-quartz iron-formation in the stratigraphically lower northeastern part of the exposure gradually changes to specularite-quartz iron-formation in the stratigraphically higher southwestern part of the exposure. Note the coarseness of grain sizes as compared with grain sizes in the jaspilite at Jasper Knob. The coarse grain sizes ~~are~~ result of recrystallization of the iron-formation in the sillimanite zone of regional metamorphism (see map of metamorphic zones). Another result of high-grade metamorphism here was the growth of grunerite along contacts between layers of magnetite and quartz, by reactions between these minerals, by silicification of siderite, or by recrystallization of a low-temperature iron silicate such as minnesotaite. The quartz-magnetite iron-formation has thin, even bedding, whereas the quartz-specularite iron-formation has wavy, irregular bedding. Some of the red quartzite (jasper) layers in the specularite-quartz iron-formation (Jaspilite) contain hematitic oolites. The thin and even bedding in the magnetite-quartz iron-formation indicates deposition in comparatively deep water under quiet conditions. As the iron-formation was laid down the basin of deposition became shallower and wave or current action became effective in disturbing bedding and forming oolites. The shallower sea water became more highly oxygenated, and magnetite-silica deposition gave way to hematite-silica deposition. The interbedding of wavy-bedded jaspilite and even-bedded magnetite-quartz iron-formation in the transition zone suggests fluctuations in the depth of sea water during deposition and a very close correlation between shallow water effects on bedding and the state of oxidation of the iron-formation. The evidence for primary oxide facies of iron-formation is more convincing here than at Jasper Knob. (In referring to magnetite and hematite as primary minerals, it is recognized that both may in fact have been preceded by less-stable oxides or hydroxides of iron of turly depositional origin that were converted to magnetite or hematite during diagenesis.)

Stop 9.

Outcrop on east side of Michigan Hwy. 95, approximately 1,000 feet south of bridge over Michigamme River, 1/2 mile west of Republic.

(See geologic map of Republic Mine area in district guidebook by B. H. Boyum)

Stop 9. -- continued

Tightly folded schist which is stratigraphically a part of the Michigamme Slate is exposed here in the axial region of the Republic syncline, a short distance northeast of the principal synclinal axis. The northwest-plunging axes of the minor folds in this outcrop conform to the plunge of the whole syncline. The outcrop is within the Republic node of high-grade regional metamorphism (see map of metamorphic zones.) The rock, which originally was probably argillite and siltstone of graywacke composition, has been metamorphosed to medium- and coarse-grained schist. The schist is well bedded and different layers are rich in biotite and quartz, biotite and garnet, or amphibole (in part grunerite). Garnet porphyroblasts are densely concentrated in some layers. High-grade metamorphic rocks in the Michigamme Slate, such as these, show clearly that the most recent major metamorphism of the area was post-Michigamme. The absence of sillimanite in this outcrop within what is defined as the sillimanite zone is due to lack of beds of appropriate composition. Sillimanite has been found in erratic boulders of Michigamme Slate in this area.

Stop 9a.

Outcrops on both sides of Michigan Hwy. 95, about 2 miles north of Republic, in NW1/4 sec. 32, T.47 N., R. 29 W.

Some representative varieties of lower Precambrian (pre-Animikie) granitic gneiss of the Republic area are exposed here. These rocks comprise part of the Southern Complex described in U. S. Geological Survey Monograph 28.

The gneiss is cut by several completely metamorphosed thin biotitic and amphibolitic dikes, which were probably diabase at the time of emplacement. The present metamorphic mineralogy of the dikes, as well as the structural setting of some of the dikes, is significant in dating the gneiss as early Precambrian in age. Southeastward-trending amphibolitic dikes occur near the north and south ends of the exposure. In the gneiss between these, 2 northeast-trending biotitic dikes occur on the west side of the highway, and a north-northeast-trending amphibolitic dike with biotitic borders occurs on the east side of the highway. The northeast-trending dikes clearly transect the southeast-trending foliation of the gneiss, and so are believed to postdate the foliation. The present mineralogy of the dikes is a product of the high-grade late middle Precambrian (post Michigamme) metamorphism of the Republic area. Therefore, the emplacement of the dikes is dated as earlier than late middle Precambrian (late- or post-Animikie) metamorphism as well as later than the gneissic foliation. The high-grade metamorphism of these dikes and of the metasedimentary rocks of the Republic area therefore cannot have been a result of igneous activity associated with the formation of the gneiss, as has been advocated by some geologist. The assignment of a post-Animikie age for the granitic gneiss is therefore disproved, and the term "Republic Granite", with a supposed post-Animikie age, has been abandoned, with concurrence of the original proponent of the term (C. A. Lamey). The granite gneiss is pre-Animikie in age, as originally concluded by Van Hise and Leith; the only post-Animikie granitic rocks are relatively small masses of unfoliated granite and pegmatite.

Stop 9a. -- continued

The apparent "absolute" age of the pre-Animikie granitic rock is about 2600 million years, whereas that of the post-Animikie pegmatite is about 1800-2000 million years. These rocks are to be compared with the unmetamorphosed Keweenaw dikes in the region, which have an age of about 1100 million years.

Stop 10.

Outcrop at sharp bend in road on hill, immediately north of Champion, NW1/4 sec. 32, T. 48 N., R. 29 W.

The Bijiki Iron-Formation Member of the Michigamme Slate is exposed here on the south limb of the Marquette synclinorium, about 1/4 mile south of the major axis and about 3/4 mile north of the south margin. The total width of the synclinorium in this vicinity is only about 2-1/4 miles. This exposure occurs in the staurolite zone of regional metamorphism that rings the Republic sillimanite node (see map of metamorphic zones).

Original laminations, ranging from less than a millimeter to several centimeters in thickness, are remarkably well preserved in spite of the complete recrystallization and nearly completely new mineralogy resulting from metamorphism. The layers now consist of felted mattes of grunerite with minor magnetite and quartz. In one zone approximating bedding in attitude, grunerite has formed spherulites which have diameters up to 3 millimeters. Thin veins of grunerite cut the rock in several places.

The premetamorphic iron-formation might have been rich in either iron carbonate or iron silicate (greenalite?). Either the silication of original siderite by the combining of its iron with chert and the loss of its carbon dioxide, or the recrystallization of low-temperature iron silicate could have produced the grunerite. The fact that cores of relict quartz (chert) are present in some layers suggests that the siderite + quartz reaction predominated; the quartz cores represent excess silica over that needed to react completely with original siderite.

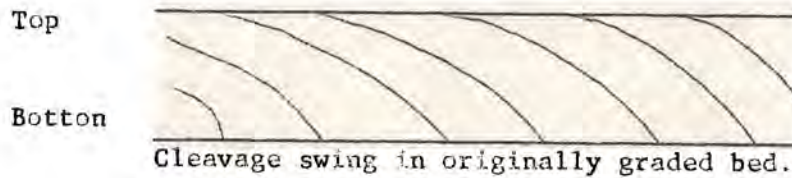
Stop 11.

Outcrop, about 2-1/2 miles southwest of village of Michigamme, approximately 250 feet north and 250 feet west of the southeast corner of sec. 35, T. 48 N., R. 31 W.

Staurolite schist which is stratigraphically part of the Michigamme Slate is exposed here near the west end of the Marquette synclinorium, and near the northwest edge of the staurolite metamorphic zone that surrounds the Republic node (see map of metamorphic zones). Original bedding is shown best by staurolite-rich layers, in places at an angle to cleavage. The size of the staurolite porphyroblasts varies from

Stop 11. -- continued

one layer to another, reaching a maximum diameter of about one half inch. Between the staurolite-rich beds, which represent original shale layers, are beds of fine- to medium-grained graywacke granulite. Some beds show an ill-defined gradation from granulite to staurolite schist that probably represents original graded bedding. Elsewhere in the region [redacted] graded bedding is revealed by a cleavage swing; cleavage that is parallel or nearly so to bedding in the (originally) fine-grained tops of beds swings so as to form a definite angle to bedding in the (originally) coarser-grained lower parts of beds.



SUGGESTIONS TO PARTICIPANTS

Marquette Range Field Trip

May 9, 1964

Obviously, the primary purpose of this field trip is to give you the opportunity to see the area's most significant outcrops. As corollaries, we assume that the scenic wonders of Marquette County and the jolly comraderie of bumping around on back roads in a bus are of secondary importance to you. If you follow us so far, and agree, read on!

Thirteen stops have been planned, which vary from 15 to 55 minutes in length. If all of these stops are made according to our schedule, you will be spending your time as follows:

Riding (about 100 miles)	275 minutes
Getting from your bus seat to the rocks	55 "
Getting back to your seat	55 "
Lunch	30 "
<u>LOOKING AT THE ROCKS</u>	230 minutes or about 18 minutes per stop
	645 minutes

If there are 100 of us and each of us delays the group only 10 seconds just once sometime during the day (and that's a cinch if we aren't careful), that will mean a cumulative delay of about 17 minutes. In order to compensate for this, we will have to eliminate a stop.

THEREFORE WE STRONGLY URGE YOU TO:

1. Remember which bus you're on and don't change buses unless you trade with someone.
2. Read through your guide material prior to your arrival at each stop.
3. When the bus stops, clear the bus quickly. The buses will have to be turned around at some of the stops.
 - a. Please do not talk while unloading--talking unavoidably causes delays.
 - b. Those in the aisle seats--get into the aisle as soon as you can--avoid the "after you, my dear Gaston" routine.
 - c. Those in the window seats--slide to the aisle seat as soon as it's vacant and then get into the aisle, as above. Don't expect those already in the aisle to wait while you try to slide over and get into the aisle in one motion.
 - d. Once you're in the aisle, walk as quickly (and safely) as you can to the exit. Don't stop to let others into the aisle because you will not only slow yourself down but those behind you.

- e. If you find as you are getting off that there is consistently more room between you and the person in front of you than there is between you and the person behind you, the inescapable conclusion is that you are holding things up. In this case, get back to the bus a little earlier next time so that you can get a window seat. Then, at the next stop, you can go at your own pace after the speedsters have left.
4. As soon as you're on the ground, get away from the door area, at least 20 feet away, before you slow down.
5. If you want to stop and chat, step off the trail so others can get by.
6. Gather promptly near the group leader.
7. A warning (bus horn?, whistle?, scream?) will be sounded 2 minutes before the final signal to get back to the bus. If you've seen your fill and/or want to take it easy, you should start back immediately.
8. At the final signal to board, go back to your bus immediately. If there's a pile up behind you, let them pass and then start back earlier next time.
9. Don't stop within 20 feet of the bus door--get in; keep the steps full, no talking, etc.
10. Take the first aisle seat that's vacant.
11. Move over to the window seat immediately.
12. Don't save a seat for anyone and don't expect to get the same seat twice yourself unless you get back early enough each time to re-stake your claim.
13. Lunch will be served buffet style--keep moving at the serving table and particularly after you've been served.

GOOD LUCK--HOPE WE CAN MAKE ALL 13 STOPS----- ITS UP TO YOU

Your Committee

