

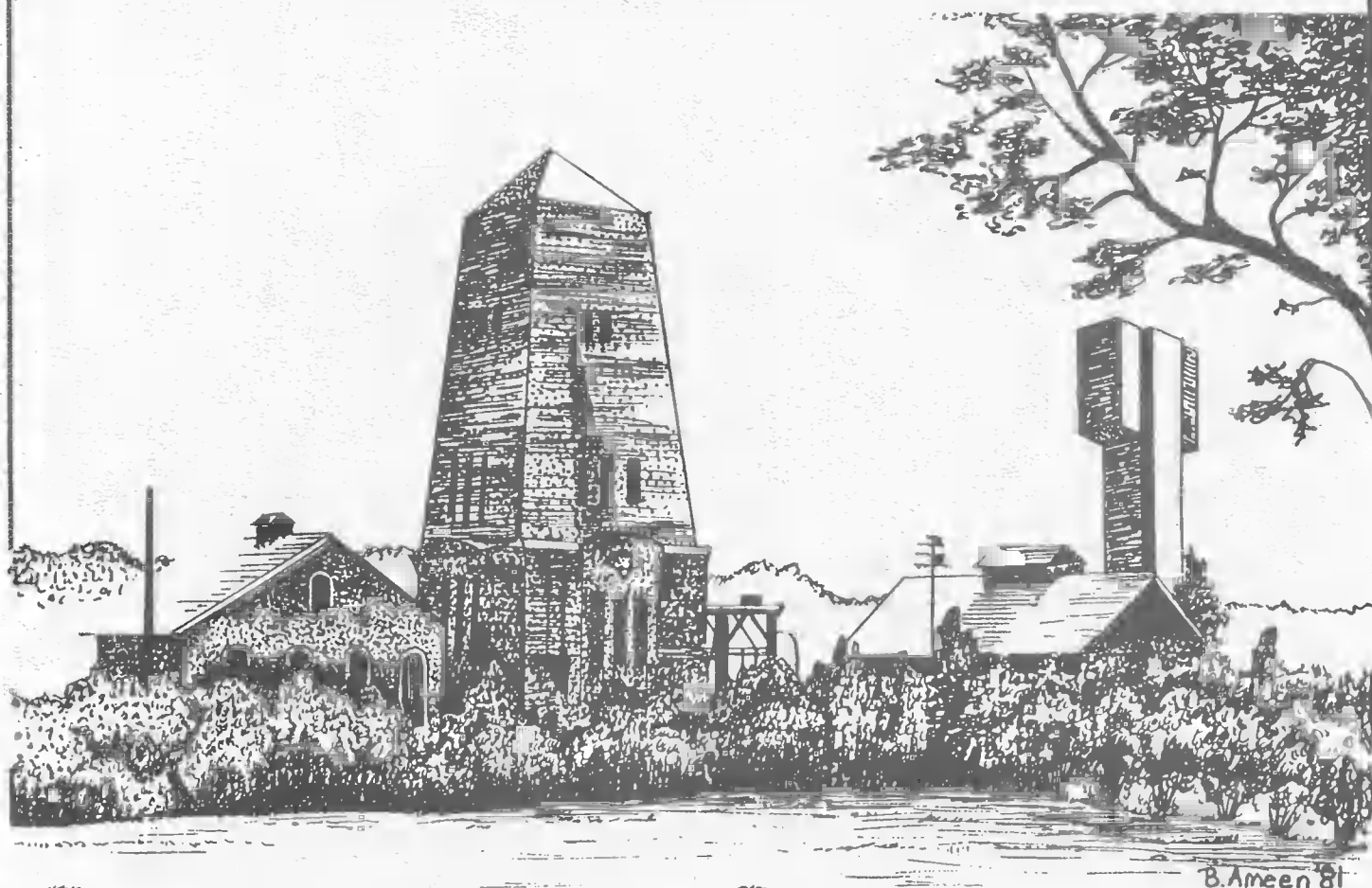
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Cover: Line drawing of Scandinavian-style headframe and modern headframe at Cleveland Cliff's Cliff shaft iron mine, Ishpeming, Michigan.

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Geological Overview of the Marquette Greenstone Belt, Michigan

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INTRODUCTION

The name Marquette Greenstone Belt is applied to the belt of dominantly Archean volcanic rocks which underlies an area of about 125 mi² (325 km²) in northern Marquette County, Michigan (Figure 1). The belt occupies the eastern part of the northern complex, an extensive terrane of Archean granite-greenstone (750 mi²; 1950 km²) north of the Marquette trough. Lower Proterozoic sediments, which fill the Marquette trough and overlie the complex, bury the Great Lakes Tectonic Zone, a major regional Archean structural zone described by Sims (1980). The Marquette Greenstone Belt represents the southwestern extension of the Wawa Subprovince of the Superior Geologic Province of the Canadian Shield as defined by Card and Ciesielski (1986). The specific focus of this overview (and of the accompanying field trips) is the greenstone belt, which occupies about one-fifth of the entire Archean northern complex.

The Marquette Greenstone belt consists of several thousand feet of subaqueous mafic to silicic flows and pyroclastics, and volcanoclastic sediments. These are intruded by gabbro and rhyolite dikes and by granitoid plutons. The belt also includes two intrusive peridotite bodies, one in vicinity of the Ropes Mine and the other at Presque Isle. All these rocks are Archean, about 2700 to 2500 Ma old (Morgan and DeCristoforo, 1980; Trow, 1979). Their metamorphic grade ranges from greenschist to amphibolite facies and they have been subjected to multiple deformation during the Archean. There are numerous gold and base metal occurrences throughout the belt (Bodwell, 1972) but the Ropes Mine is the most significant to date (Brozdowski, this volume; Bornhorst and others, 1986; Brozdowski and others, 1986). The Archean rocks are unconformably overlain by

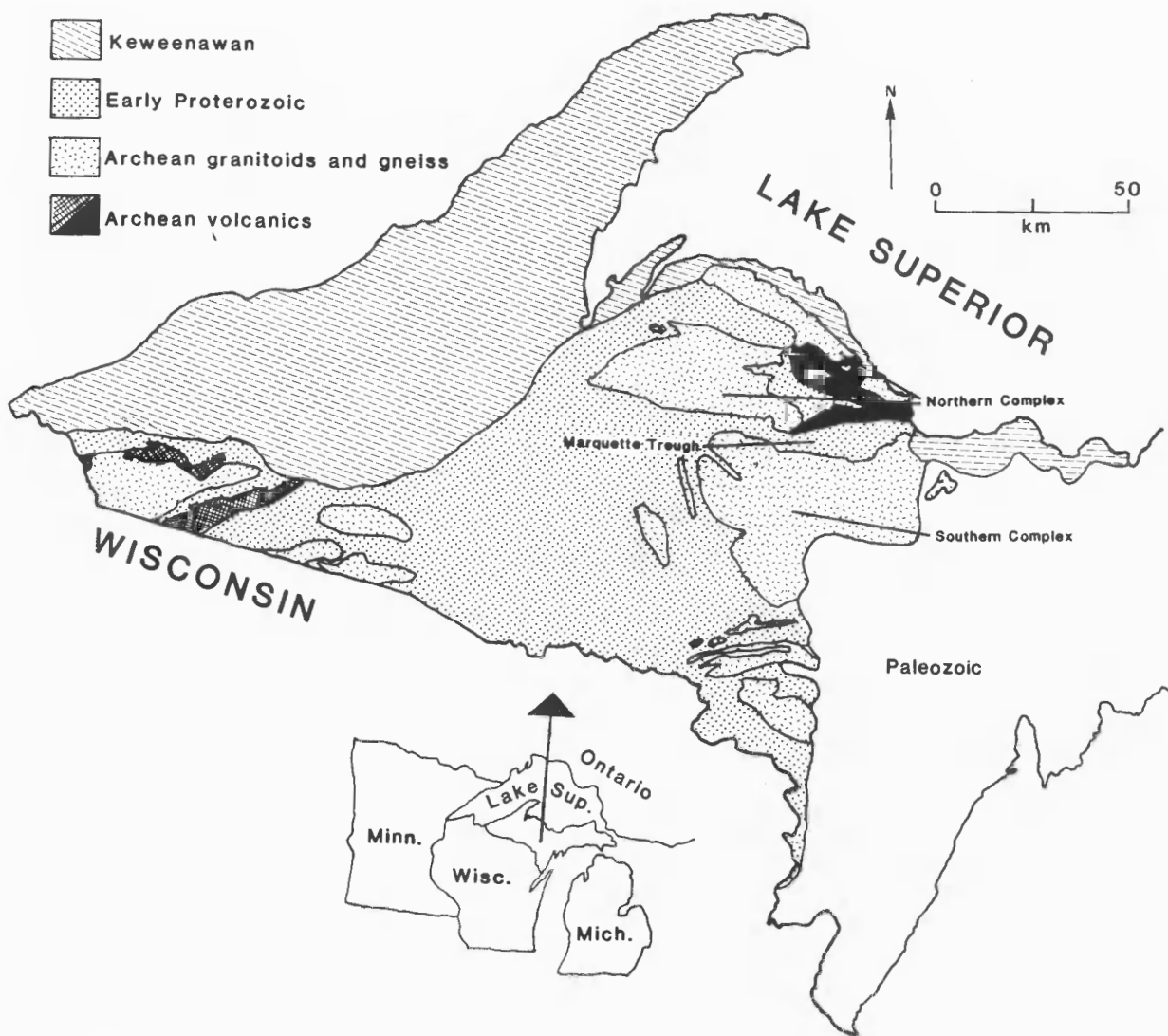


Figure 1: Regional geological setting of the Marquette Greenstone Belt which is shown in solid black.

and, in fault contact with, Lower Proterozoic sediments.

The name Ishpeming Greenstone Belt was proposed for these same rocks by Morgan and DeCristoforo (1980). However, this name is abandoned here in favor of Marquette Greenstone Belt because these Archean rocks do not crop out in Ishpeming (Lower Proterozoic sediments crop out in Ishpeming) whereas they do crop out in the City of Marquette. Further, the belt is located in northern Marquette County.

The rocks of the belt have been studied and discussed by numerous geologists. For a historical background the reader is referred to the work of Morgan and DeCristoforo (1980). This overview is based on work by the author and his students, and on work by Gair and Thaden (1968), Puffett (1974), Clark and others (1975), Cannon and Klasner (1977), and on the geological studies summarized by Baxter and MacLellan (this volume).

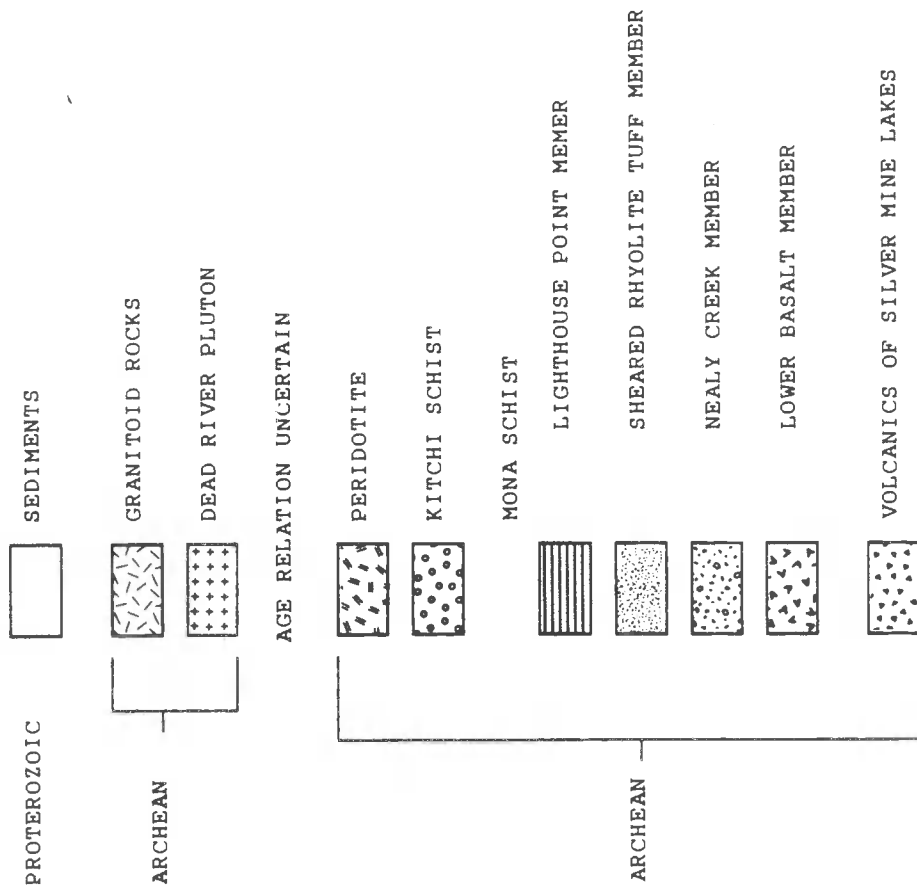
STRATIGRAPHY

As documented by the literature from other parts of the Superior Province, stratigraphic correlations across regional faults or shear zones are quite tenuous and subject to error. The stratigraphy of the Marquette Greenstone Belt will be discussed in two separate parts because the belt is traversed obliquely by the Dead River Shear Zone, a probable major fault (Figure 2). For purposes of description, the greenstone belt has been subdivided into a northern and a southern part; other faults necessitate that the southern part be further divided into an "eastern two-thirds" and a "western one-third".

Northern Part

The rocks of the northern part of the belt have been described by Baxter and MacLellan (this volume). The rocks are dominated by pillowed and massive basalt lava flows with interbedded mudflow breccias and iron-formations; this assemblage has been named the Volcanics of Silver Mine Lakes (Figure 2). These rocks are cut by dikes and sill-like bodies of gabbro and all are cut by dikes of rhyolite

LEGEND



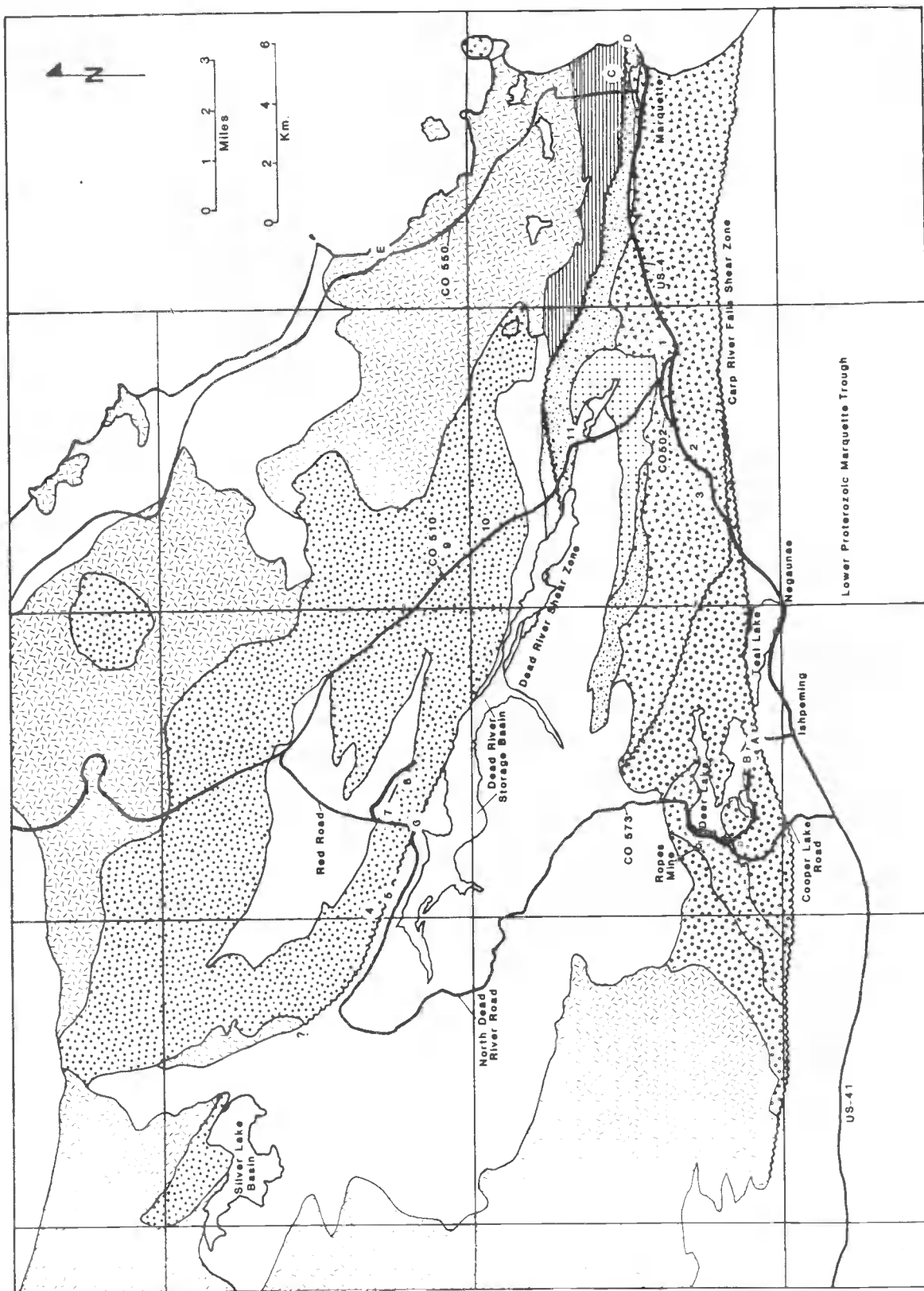


Figure 2: Geology of the Marquette Greenstone Belt, Michigan. Southern extents of the Dead River and Carp River Falls Shear Zones are shown. Numbers and letters represent stops for field trips (this volume). Compiled from: Cannon and Klasner (1977), Clark and others (1975), Puffett (1974), Bodwell (1972) and Gair and Thaden (1968).

and plutons of granodiorite. Granitoid plutons intrude the northern part of the greenstone belt to the northeast (see Day 2 Road Log, Stop E).

The granitoid rocks of the Marquette Quadrangle were mapped as Compeau Creek Gneiss by Gair and Thaden (1968). This name has also been assigned more recently to similar-looking crystalline rocks in the region south of the Marquette trough (Figure 1), and in essence, signifies "undifferentiated plutonic rocks of Marquette County". The name Compeau Creek Gneiss should be used only in that context or perhaps, be abandoned.

Southern Part

The rocks of the southern part of the belt, south of the Dead River Shear Zone, have been mapped by Gair and Thaden (1968), Puffett (1974), Clark and others (1975), and Cannon and Klasner (1977). Much of the following is based on their work. The major lithologic units (Figure 2) in the southern part of the belt are: Mona Schist, Kitchi Schist, Deer Lake Peridotite, Dead River Pluton and other unnamed granitoid plutons (mapped as Compeau Creek Gneiss and as granite).

Relative age relations among these major lithologic units are uncertain. The contact between the Mona and Kitchi Schists was mapped as a shear zone by Clark and others (1975). In addition, stratigraphic top direction within a few miles of the contact indicates that Mona Schist faces NE whereas the Kitchi Schist faces SE. Rossell (1983) has suggested that the contacts of the Deer Lake Peridotite are structural and not stratigraphic, making age relations uncertain. Although contacts between the plutonic rocks and volcanics rocks are commonly faults or shear zones, the plutonic rocks in close proximity to the greenstone belt can be interpreted to intrude the volcanics, based on smaller intrusive relationships and contact metamorphic features.

In view of the fact that faults complicate the study of the stratigraphy of even the southern part of the greenstone belt, it is necessary to resort to

describing the stratigraphy of the even smaller "eastern two-thirds" and "western one-third" areas.

Eastern Two-Thirds. The eastern two-thirds of the southern part of the belt consists of the Mona Schist (Figure 2). This name should perhaps be modified in the future to the "Mona Group" because the Mona Schist can be subdivided into units (currently termed members) at 1:24000 scale which should be elevated to formation status. In addition, the rocks that are mapped as the Mona "Schist" have an identifiable protolith and consequently, according to the North American Code of Stratigraphic Nomenclature, the parent lithology term should be used in the name instead of schist. Nevertheless, for present purposes the term Mona Schist will be retained as will the currently recognized four members: Lower Member, Nealy Creek Member, Sheared Rhyolite Tuff Member, and Lighthouse Point Member.

The Lower Member of the Mona Schist consists mainly of subaqueous massive and pillowed tholeiitic basalt lava flows (see Day 1 Road Log, Stops 1 and 2, this volume) with minor interbedded volcanoclastic and tuffaceous rocks. The member crops out in a 25 mi² (65 km²) area and is over 10,000 feet (3300 m) thick, assuming there is no structural repetition. Stratigraphic top direction in the Lower Member is to the north.

The Nealy Creek Member is considered to overlie the Lower Member. It consists of a variety of quartz-chlorite-sericite-feldspar schists which crop out in a 7 mi² (18 km²) area. The schists appear to be mostly greywacke and shale (see Day 1 Road Log, Stop 11, this volume), but in general the schistose texture prevents recognition of volcanoclastic or tuffaceous textures. This member (perhaps 3000 feet (1000 m) thick) is the only significant sedimentary unit in the greenstone belt.

The Sheared Rhyolite Tuff Member is considered to overlie the Nealy Creek Member. It consists of light-colored, porphyritic volcanic rocks which crop out in

a 1.3 mi² (3.4 km²) area. The common lithology consists of tabular fragments of porphyritic rhyolite surrounded by fine-grained matrix of quartz, sericite and chlorite. Phenocrysts are quartz and feldspar, and make up 10 to 50 percent of the rhyolite (Puffett, 1974). In some outcrops there are granitic fragments. This rock was interpreted by Puffett (1975) as an intensely deformed pyroclastic deposit.

The Lighthouse Point Member lies north of the Nealy Creek Member and crops out in a 7 mi² (18 km²) area. This member encompasses two different lithologies: relatively coarse-grained amphibolite, and layered amphibolitic schist (see Day 2 Road Log, Stops C and D, this volume). Morgan and DeCristoforo (1980) have interpreted the coarse-grained amphibolite to be gabbro. The layers in the layered amphibolite are interpreted as flattened pillows and the material between the layers is often well-foliated. The flattened pillows may be due to primary processes or to deformation. This author suggests that much of the flattening is due to high strain.

Western One-Third. The western one-third of the southern part is underlain by Kitchi Schist and Deer Lake Peridotite (discussed under Intrusive Rocks) (Figure 2). The name "Kitchi Schist" should likewise be changed to "Kitchi Group". The Kitchi Schist crops out in a 12 mi² (30 km²) area and consists of three dominant lithologies. To the east of the Deer Lake Peridotite it consists of quartz-sericite phyllites and schists, commonly containing feldspar phenocrysts and lithic fragments, (see Day 2 Road Log, Stop A, this volume) and coarse breccias (see Day 2 Road Log, Stop B, this volume). The phyllites and schists are andesite to dacite in composition and are interpreted as interbedded pyroclastic fall and flow deposits, volcanoclastic sediments, and lava flows. The coarse breccias consist of porphyritic andesite-dacite clasts surrounded by quartz-sericite-chlorite matrix. The breccias are mostly poorly sorted, but locally along the south shore of Deer Lake layering is conspicuous (Brozdowski, 1988, personal communication). They

are interpreted as subaqueous mudflows and pyroclastic flow deposits. To the west of the Deer Lake Peridotite, the Kitchi Schist consists of mafic volcanic and gabbroic rocks which may underlie the intermediate composition volcanic rocks to the east (Brozdowski, this volume; Brozdowski and others, 1986). Stratigraphic top direction in the Kitchi Schist is consistently south (Brozdowski, 1988, personal communication).

Intrusive Rocks. The Deer Lake Peridotite, now predominantly a serpentinite, crops out in a 2 mi² (5 km²) area (see Field Guide to Callahan Mining Corporation Ropes Mine Property, this volume), and is surrounded by Kitchi Schist (Figure 2). Serpentine pseudomorphs after olivine and pyroxene are common and the rock contains euhedral magnetite. In some serpentinite there are textures which are indicative of cumulate origin. Foliated serpentinite occurs near the contacts and at the Ropes Mine. Near the Ropes Mine, the serpentinite is altered also to a talc-carbonate rock (Bornhorst and others, 1986). Bornhorst and others (1986) interpret the Deer Lake Peridotite as an discordant intrusive body with structural contacts whereas Brozdowski and others (1986) agree on the overall intrusive nature of the body but interpret its contacts as being more concordant and hence more sill-like.

Dikes of Archean gabbro cut the Mona and Kitchi Schists. Where recognized, these intrusions were mapped most commonly as metadiabase of uncertain age relations (Puffett, 1974; Gair and Thaden, 1968). Dikes of rhyolite cut the basalt and gabbro, but the age relationship between the rhyolite dikes and the granitoid plutons is less clear; only a few similar-appearing rhyolite dikes cut the plutons. The textures of the rhyolite dikes are porphyritic (most common), aphanitic, and granular (least common). Porphyritic rhyolite is composed of phenocrysts of quartz with or without feldspar set in a very fine-grained groundmass. The granular rhyolite dikes show a textural continuum to granitoid plutons. Undifferentiated granitoid plutons (southwest part of Figure 2) and the Dead

River Pluton cut the greenstone belt. The Dead River Pluton is a composite pluton and consists of granodiorite, diorite, and syenite (Puffett, 1974). The southwestern granitoid plutons have been poorly studied, but most are probably granodiorite. At the Peppin Prospect (3.5 miles NW of the Ropes Mine), Boben (1986) described a trondhjemite. The Archean granitoid plutons are interpreted as syn- to post-tectonic.

GEOCHEMISTRY

There are now over 200 major and trace element analyses from the Marquette Greenstone Belt. Most trace element data have been determined by XRF and about 20 by INAA. Geochemically the basaltic lava flows and gabbroic intrusives are tholeiitic, whereas the andesite to dacite fragmental rocks and rhyolite intrusives are calc-alkalic. Although variable, the chemical compositions of the basalts and gabbros overlap to the extent that they must be considered compositionally similar, and to have similar petrogenetic histories.

To demonstrate that the belt is dominantly basalt with a scattering of compositions towards rhyolite, Bornhorst and Baxter (1987) multiplied the surface area of each major unit of the greenstone belt (as an indication of volume relations) by the representative average chemical composition. Of the lesser number of silicic rocks, more compositions fall near the andesite-dacite boundary than on either side, i.e., the belt is very mildly bimodal.

The few analyses of granitoid plutonic rocks suggest that the granitoids are calc-alkalic in affinity. On a variety of compositional diagrams, the rhyolite dikes that cut the greenstone belt lie on similar trends with the plutonic rocks and overlap the chemical composition of the more silicic plutons. The rhyolite dikes are interpreted as late-stage, generally more evolved parts of the plutons that intrude the greenstone belt.

METAMORPHISM

The rocks of the greenstone belt were metamorphosed from greenschist to

amphibolite facies during the Archean. During the Penokean orogeny, the Archean rocks were subjected to greenschist facies metamorphism and, in areas of amphibolite facies, this Penokean metamorphism is denoted by retrograde assemblages. Archean regional greenschist facies was elevated to the amphibolite facies in relatively restricted areas.

STRUCTURE

Archean structural geology of the Marquette Greenstone Belt is dominated by E-W, NW-SE, to N-S faults, but some data suggest that the belt has been subjected to multiple deformations. For example, from north of the Dead River Storage Basin, Johnson and others (1987) have described an Archean, steeply-plunging, synformal anticline with dimensions on the order of miles. This fold requires at least two periods of Archean deformation. Similarly, the Mona-Kitchi structural relationship described earlier requires at least two periods of Archean deformation.

The Archean rocks are overlain by Early Proterozoic supracrustal rocks which were deformed during the Penokean orogeny (1900 to 1800 Ma). Although reactivation of Archean structures during the Penokean orogeny can be documented clearly, various lines of evidence suggest that most of the structure in the greenstone belt represents Archean deformation.

Local Faults and Shear Zones

In the Marquette Greenstone Belt most stratification dips steeply; dips near vertical ($\pm 10^\circ$) are quite common. The rocks are variably foliated, but on both a local and regional scale there are linear zones along which the foliation is better developed than in surrounding rocks. These zones of higher strain may be faults or shear zones. Where stratigraphic units are offset they are mapped as faults.

North of the Dead River Storage Basin many high strain zones are too small to show at 1:6000 (1 inch equals 500 feet). Faults are of brittle-ductile and ductile types, and displacement may be mostly vertical. These faults are also of

two general ages: older roughly E-W faults truncated by younger N-S faults (Johnson and others, 1987).

South of the Dead River Storage Basin, Clark and others (1975) interpreted the contact between the lithologically distinct Kitchi and Mona Schists to be a shear zone (Figure 2), and contacts of the Deer Lake Peridotite have also been interpreted as either faults or shear zones (Clark and others, 1975; Rossell, 1983).

Regional Faults and Shear Zones

The Marquette Greenstone Belt is affected by two regional Archean shear zones (Figure 2). Extending along the entire southern boundary of the greenstone belt is the Carp River Falls Shear Zone (Puffett, 1974). Rocks along this shear zone are both intensely foliated and altered (see Day 1 Road Log, progression from Stops 1 to 3, this volume). However, the full width of the shear zone is not known since a part of it was reactivated during the Penokean orogeny, juxtaposing more altered and sheared Archean rocks against less deformed Early Proterozoic sediments. The exposed width of this zone is up to 1500 ft (450 m) as documented by detailed mapping (Brozdowski, 1988, personal communication). Since this shear zone is cut by much less deformed mafic dikes of Archean age (Baxter and Bornhorst, 1988), it must be Archean in age. This shear zone may be part of the Great Lakes Tectonic Zone of Sims (1980).

The second major structural zone cuts through the middle of the greenstone belt and is termed the Dead River Shear Zone (Puffett, 1974) (Figure 2). As recognized by Puffett (1974), the shear zone lies within the Sheared Rhyolite Tuff Member of the Mona Schist (near the east end of the Dead River Storage Basin). In this area detailed gravity and magnetic data are consistent with the interpretation of a steeply dipping shear zone (Weeks, 1987). The Dead River Shear Zone can be extended to the west it was reactivated during the Penokean orogeny, juxtaposing Archean and Early Proterozoic rocks in a manner similar to the Carp River Falls Shear Zone. In the west, the existence of the shear zone is indicated

by well-foliated and altered Archean rocks along the Archean and Early Proterozoic contact (see Day 1 Road Log, Stop 5, this volume). It is proposed that the eastward extension of this shear zone follows the Lighthouse Point Member of the Mona Schist which is interpreted as having been subjected to high strain (see Road Log Day 2, Stops C and D). Thus, the Dead River Shear Zone represents a NW-SE trending fault, with unknown displacement, that bisects the Marquette Greenstone Belt.

PRECIOUS METAL MINERALIZATION

Of the numerous base and precious metal occurrences in the belt (Bodwell, 1972), the Ropes Mine is the most significant orebody to date (Figure 2). The Ropes Mine has been described by Bornhorst and others (1986) and Brozdowski and others (1986) and in this volume by Brozdowski. It has been mined for Au and Ag and has a Au/Ag ratio of about 1 to 5. Metallic minerals are dominated by pyrite, with lesser other sulfides such as tetrahedrite, galena, and chalcopyrite. Certain parts of the Ropes Mine show a good correlation between abundance of Au and fine pyrite (Brozdowski, this volume). Non-metallic alteration minerals are dominated by quartz and carbonate with varying amounts of sericite, chlorite and talc. The ore host rock for the Ropes orebody is interpreted by Bornhorst and others (1986) and Brozdowski and others (1986) as a dacitic volcanoclastic rock within the Deer Lake Peridotite. Both Brozdowski and Bornhorst agree that the mineralization is epigenetic, but differ in their interpretation of mechanism of emplacement. Brozdowski and others (1986) suggest that precious metals were concentrated by hydrothermal fluids related to emplacement of peridotite sills (Deer Lake Peridotite). Bornhorst and others (1986) suggest that the orebody was syntectonic and that hydrothermal fluids followed a zone of relatively high strain, a shear zone. Brozdowski (this volume) describes a structural genetic model for the Ropes orebody.

Other less important occurrences of mineralization present as disseminations

and in quartz veins, are associated with all the major Archean rock types. Most of the occurrences are interpreted as epigenetic, but at some poorly studied localities the mineralization may be syngenetic. The description that follows applies to epigenetic mineralization.

Mineralization is commonly spatially associated with faults and shear zones, and is interpreted as syn- to post-tectonic. Sulfide minerals are significant indicators of precious metal mineralization. Pyrite occurs as disseminations and in quartz and quartz-carbonate veins. Pyrrhotite, chalcopyrite, and arsenopyrite are less abundant than pyrite. In studies carried out at Michigan Technological University, no anomalous Au or Ag values were obtained from any sample of rock or quartz vein that was free of sulfides. Sphalerite and galena are found at some occurrences, and these minerals tend to be more commonly associated with anomalous Ag, whereas the yellow sulfides are associated with Au. Abundance of sulfides in a rock, as measured by abundance of sulfur, is poorly correlated with the abundance of Au. Quartz, carbonate, chlorite, and sericite occur as wall-rock alteration minerals; quartz and carbonate also occur as vein minerals associated with precious metal anomalies.

The present data permit the tentative suggestion that there appear to have been at least two major pulses of mineralization. An early pulse resulted in pervasive quartz and carbonate alteration and was accompanied by gold, pyrite and other yellow sulfide minerals, and abundant chlorite and sericite. Quartz-carbonate veins are associated with this early pulse. Detailed studies by Callahan Mining Corporation (Brozdowski, 1988, personal communication) indicate that significant occurrences of gold mineralization are associated with structures parallel and conjugate to layering between rock types. A later pulse of mineralization was dominated by quartz-carbonate veins containing base metal sulfides (pyrite, galena, sphalerite, with little or no Au), although the relatively abundant galena at the Ropes Mine may be an exception. The extent of country rock alteration associated with this latter pulse may have been less than that associated with the earlier

pulse. At some individual prospects a paragenetic succession of metallic and non-metallic minerals can be recognized within a pulse.

SUMMARY

The Marquette Greenstone belt consists of several thousand feet of subaqueous mafic to silicic volcanic flows, pyroclastics, and volcanoclastic sediments. These are intruded by gabbro and rhyolite dikes and by granitoid plutons, all of Archean age. The belt also includes two peridotite bodies. All of these rocks have been metamorphosed from greenschist to amphibolite facies and subjected to multiple deformation. Precious metal mineralization is dominantly epigenetic. The Archean geologic history of the belt is obscured by unconformably-overlying Early Proterozoic sediments and by deformation during the Penokean orogeny.

The potential for discovery of new economic deposits of precious metals in the Marquette Greenstone Belt is denoted by anomalous Au values, quartz and carbonate veins, areas of pervasive alteration, areas of relatively abundant faults and shear zones, and overall geologic setting.

ACKNOWLEDGEMENTS

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Geological Framework of a Part of the Archean Marquette Greenstone Belt North of the Dead River Storage Basin

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INTRODUCTION

The Archean Marquette Greenstone Belt underlies approximately 125 mi² (325 km²) of northern Marquette County in Michigan's western Upper Peninsula (Figure 1). The greenstone belt is divided into northern and southern portions by a structural zone which parallels the Dead River Storage Basin (Bornhorst, this volume). The southern part of the greenstone belt and the metasediments of the Marquette Supergroup were mapped by the U.S.G.S. The northern part of the belt was partially mapped by the U.S.G.S. and the remainder was included on the 1:60,000 compilation map of the northern complex by Bodwell (1972). The aim of this paper is to briefly describe the geology of the northern part of the Archean Marquette Greenstone Belt based on detailed mapping of the southwest 25 mi² (65 km²).

Archean rocks of the northern part consist of dominantly subaqueous mafic lava flows, and minor, interbedded volcanoclastic and pyroclastic deposits of intermediate composition and iron formation. All of these rocks are assigned to the Volcanics of Silver Mine Lakes, an informal formation name used to distinguish these strata from the remainder of the Mona Schist which is situated on the southern side of the Dead River Shear Zone, an Archean structural zone with a large, but unknown, degree of movement. The volcanic package has been intruded by gabbro and subsequently by rhyolite and granodiorite of Archean age. The rhyolite is interpreted as a more evolved equivalent of the granodiorite to tonalite plutonic rocks (Bornhorst and Baxter, 1987).

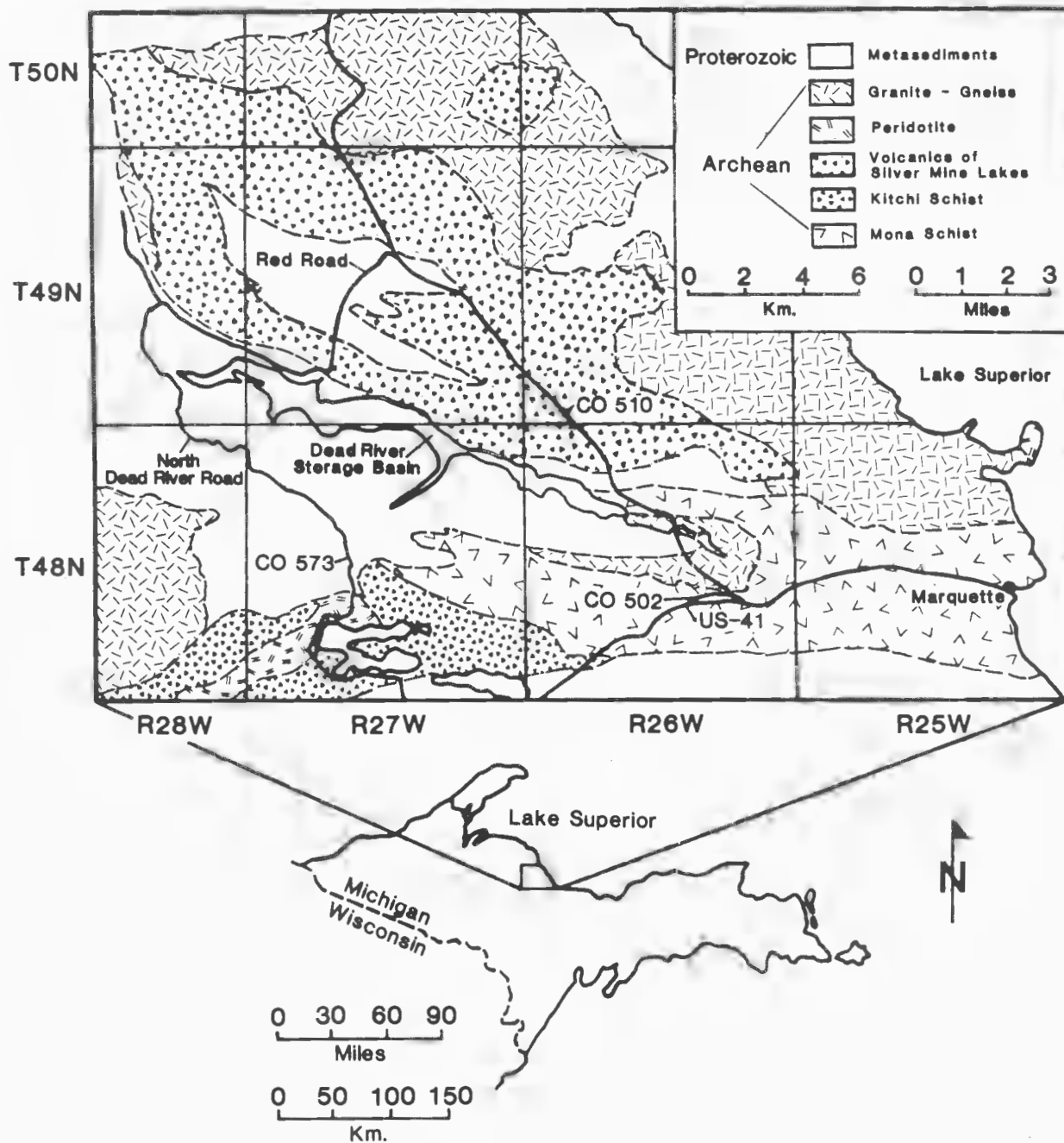


Figure 1. Regional geology and location map of the Marquette Greenstone Belt (modified from Morgan and DeCristoforo, 1980).

VOLCANICS OF SILVER MINE LAKES

The Volcanics of Silver Mine Lakes (MacLellan and Bornhorst, 1988) are named for a succession of Archean volcanic units that crop out in the vicinity of Silver Mine Lakes. Detailed mapping (MacLellan and Bornhorst, 1988; Baxter and others, 1987; Johnson and others, 1987; Owens and Bornhorst, 1985) has distinguished five members: Pillowed Basalt Member, Breccia Member of Bismark Creek, Breccia Member of Reany Lake, Iron Formation Member, and the Hill's Lake Pyroclastic Member (Figure 2). Relative ages of the members are based on the presence of pillows as top indicators in the Pillowed Basalt Member. The members are too small to be distinguished at 7½ minute quadrangle scale (1:24,000).

Pillowed Basalt Member

This member has been subdivided into three varieties, normal, foliated, and altered, based on various criteria. The contacts between these varieties are gradational.

Normal Variety. This variety is commonly dark green to green-black in color, fine-grained to aphanitic, and massive to moderately foliated (see Day 1 Road Log, Stops 6 and 10, this volume). Visible mineralogy includes very fine-grained chlorite, very fine-grained plagioclase and sericite, and rarely fine-grained amphibole. Very fine-grained plagioclase crystals often show relict igneous microlite textures. Elongate, variably flattened pillows are found locally and range from 1-8 feet (30-250 cm) in length and 3-30 inches (8-76 cm) in thickness. Some pillows show small bands of vesicles (1/16-1 inch, 2-25 mm) along the chilled margins. It is common to find interpillow void space filled with tan to gray carbonate material. In a few places, stratigraphic tops have been determined from the cusped pillow shapes.

Quartz and quartz-carbonate veins from less than 1/16 inch (2 mm) to 9 inches (23 cm) in width can be found throughout this variety. The veins can

Correlation of Archean Units

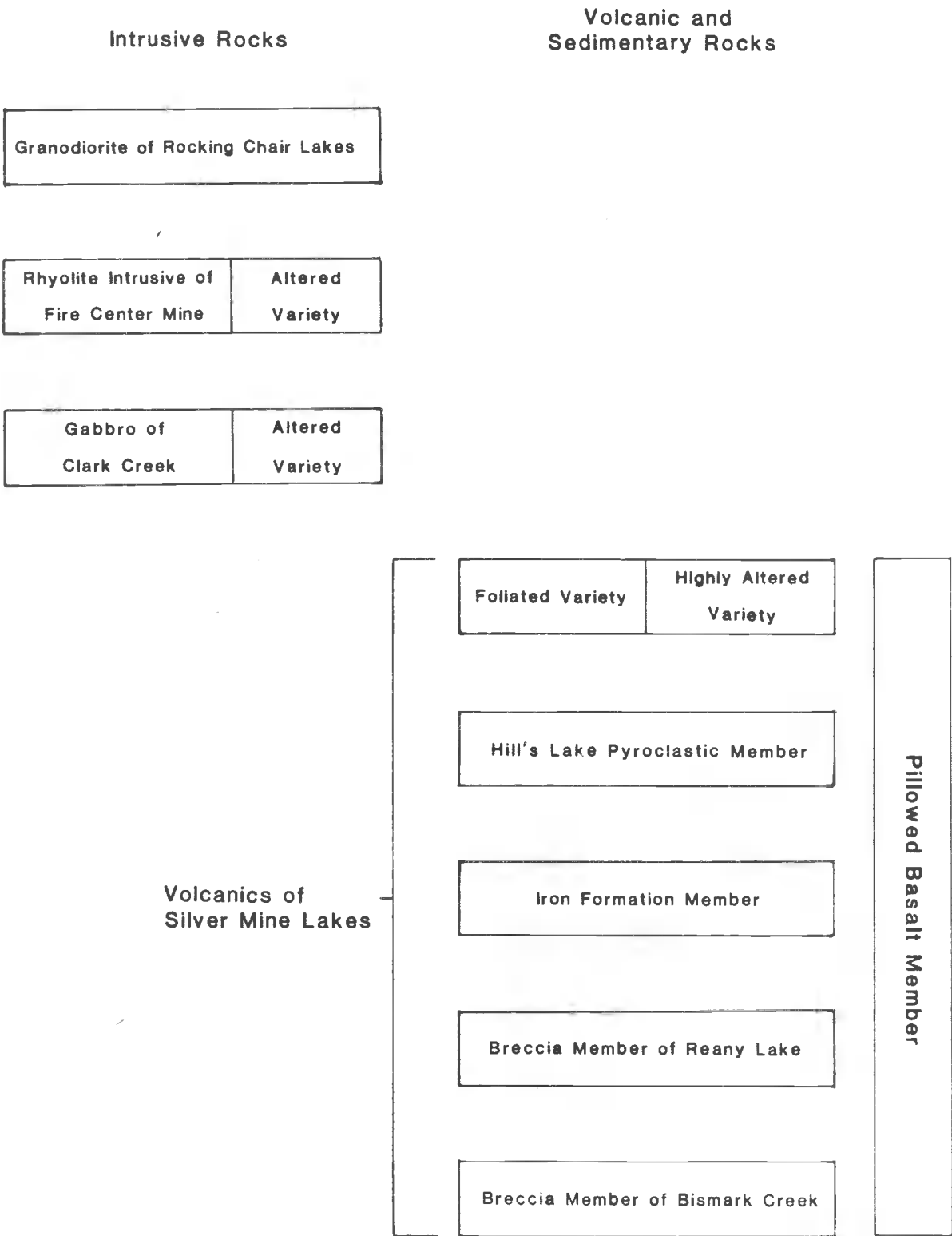


Figure 2.

carry up to 5% sulfides and there may be up to 2% disseminated sulfides in the adjacent basalts. Disseminated sulfides occur throughout much of this unit and are usually > 95% pyrite with minor amounts of chalcopyrite, pyrrhotite, and arsenopyrite.

Foliated Variety. This variety ranges in color from medium gray-black to green-black. It has an aphanitic texture, a phyllonitic to schistose fabric, and is composed dominantly of chlorite with lesser amounts of plagioclase and/or sericite, quartz and carbonate. Some exposures contain up to 40% secondary carbonate (ankerite) as the matrix of brecciated basalt. Other exposures contain alternating light and dark layers which are interpreted as tectonic layering resulting from highly elongated pillows. The alternating layers originated from darker pillow interiors surrounded by lighter colored pillow rinds. Some outcrops may also have originally been basalt tuffs and the layering may reflect highly elongated lithic fragments. Disseminated pyrite is found throughout this variety and can occur locally in concentrations up to 30%.

Highly Altered Variety. The highly altered variety of the Pillowed Basalt Member is dark to light gray in color and takes on a green hue near the gradational contact with the normal, less altered variety (see Day 1 Road Log, Stops 4 and 5, this volume). The basalt is aphanitic to very fine-grained and is composed of varying quantities of chlorite, carbonate, sericite, plagioclase, and quartz. The rocks are predominantly chloritized, with carbonatization, sericitization, and silicification occurring in varying degrees. The fabric varies from massive to very highly foliated. Typically, the degree of foliation in this variety is as high as the foliated basalt variety. In rare cases, deformed and undeformed pillow structures can still be observed on weathered surfaces.

Disseminated mineralization is most abundant in this variety of basalt. Sulfide minerals can reach up to 20 volume percent of the outcrop, but typically average only 2-6%. Quartz and quartz-carbonate veins, similar to those found in the foliated variety, also occur in this variety. In general, both types of

mineralization are related to well foliated structural zones.

Breccia Member of Bismark Creek

The Breccia Member of Bismark Creek is located along a major NW-SE trending structural zone, the Willow Creek Shear Zone (MacLellan and Bornhorst, 1988) (see Day 1 Road Log, Stop 9, this volume). There are at least three types of clasts in this unit: boudinaged porphyritic rhyolite (similar to the Rhyolite Intrusive of Fire Center Mine), wispy gabbro, and boudinaged granodiorite. The clasts are lensoidal to elongate in shape and range from 1/2 to 3/4 inches (1-2 cm) for the lensoidal type, and up to 4-6 inches (10-15 cm) in width by 3-6 feet (1-2 meters) in length for the elongate type. Clasts are supported in an epidote-rich basaltic matrix. Both the matrix and the rhyolite clasts contain up to 5% disseminated pyrite. This unit is interpreted as a mudflow breccia.

Breccia Member of Reany Lake

The Breccia Member of Reany Lake, best exposed near Reany Lake, is a breccia with a strike length of at least 5 miles (8 kilometers) (see Day 1 Road Log, Stop 8, this volume). The unit is correlative with the Mudflow Member described by Baxter and others (1987). The breccia clasts are white, gray, or brown on both weathered and fresh surfaces, whereas the matrix weathers to a light green-tan color and is a green-black color on fresh surfaces. The lower portion of the unit contains very few large clasts and was mapped as clast-poor, whereas the upper portion contains up to 35% clasts of all sizes and was mapped as the clast-rich horizon. In some exposures, there is second clast-poor zone above the clast-rich zone.

The clast-poor horizon has equant to oblong, sub-angular to sub-rounded grains of volcanic rock which rarely exceed 1/3 inch (1 cm) in size. The matrix is medium to fine-grained, intermediate to mafic in composition, with occasional 1/16 to 1/8 inch (1-3 mm) grains of feldspar. The clast-poor horizon is interpreted as either a well-sorted mudflow or a reworked tuff deposit.

In the clast-rich horizon the clasts are matrix supported. Shapes vary from highly elongate to sub-equant and rounding from very angular to rounded. The more equant clasts are generally 1/3-4 inches (1-10 cm) across while the elongated fragments can reach lengths of up to 10 inches (25 cm). It is important to note that about 50% of the clasts are white, gray, and black cherts. This, coupled with the fact that a cherty iron-formation overlies this unit, suggests that these cherts may have formed in a volcanic vent region and were brecciated during explosive eruptions. The remaining clasts are fine-grained, porphyritic andesites. The matrix is very similar to the material in the clast-poor horizon. Therefore, we also interpret the clast-rich horizon as a mudflow breccia deposit.

Iron Formation Member

The Iron Formation Member, which overlies the Breccia Member of Reany Lake, consists of gray, dark gray, to black banded rock with alternating bands of micro-crystalline chert and magnetite, or iron-rich chert (see Day 1 Road Log, Stop 10, this volume). In some localities, the unit is a black, cherty iron formation containing up to 2-5% disseminated sulfides, mainly pyrite. These cherty layers are cross-cut by carbonate veinlets which may contain up to 20% sulfides.

At Clark Creek, the iron formation is gray in color and shows very distinctive interlayering of micro-crystalline quartz and massive magnetite. This locality also contains clots of sulfides scattered through the rock, often associated with the carbonate veins that fill tension gashes. The sulfides comprise a maximum of 5% of the whole rock.

Hill's Lake Pyroclastic Member

The Hill's Lake Pyroclastic is a breccia composed of white to tan dacite clasts in a black schistose basalt matrix. The clasts are flattened and give vertical surfaces a banded appearance. The metamorphic grade of this unit is lower amphibolite. The clasts consist of plagioclase and quartz with minor hornblende,

sericite, and epidote. The matrix is composed of hornblende, plagioclase, biotite, and garnet, with minor sericite, chlorite, tourmaline, and clinozoisite/epidote (Johnson and others, 1987).

GABBRO OF CLARK CREEK

The Gabbro of Clark Creek (MacLellan and Bornhorst, 1988) is named for gabbro intrusives that cut the Volcanics of Silver Mine Lakes near Clark Creek (see Day 1 Road Log, Stops 5, 8, and 10, this volume). The gabbro is medium to dark green-black on a fresh surface, holocrystalline, medium to very coarse-grained, and massive to strongly foliated. The mineralogy is blue-green amphibole, plagioclase, chlorite, and minor pyrite, magnetite, and pyrrhotite. The more foliated zones within the gabbro have a much higher percentage of chlorite which causes a deeper green color.

There is also an altered variety of gabbro which is medium to dark gray in color with plagioclase crystals forming augens surrounded by chlorite, carbonate, quartz, and sericite. This rock has an undulating, schistose texture on the foliation surface. The intensity of alteration is greater near zones of intense foliation.

RHYOLITE INTRUSIVE OF FIRE CENTER MINE

The Rhyolite Intrusive of Fire Center Mine (Johnson and others, 1987) has three common textural types and cuts the volcanics and the gabbro (see Day 1 Road Log, Stops 5,6, and 7, this volume). The first two, porphyritic and granular, are grouped together as the normal variety. The third is aphanitic, but since it is typically altered, it is termed the altered variety.

Quartz-porphyritic rhyolite is the most common textural type, with anhedral phenocrysts of quartz, 1/16 to 5/16 inches (2-8 mm) across. The other porphyritic type is quartz-feldspar porphyritic rhyolite, with phenocrysts of subhedral potassium feldspar and/or plagioclase as well as anhedral quartz of similar size. The matrix in both types is fine-grained to aphanitic and consists of quartz,

carbonate, feldspar, and minor sericite. Color varies from dark gray to light gray to pink. The granular type is generally light pink with roughly equidimensional quartz and feldspar grains, 1/16 to 3/16 inches (2-5 mm) across. Disseminated sulfides are present in amounts of usually less than 1%.

The altered variety is a light green to green-gray, aphanitic, schistose rock. It is identified in the field primarily by color and lack of visible grains. The rock is composed of partially recrystallized quartz, feldspar, and interstitial sericite which may define a crude foliation. There are up to 8% disseminated sulfides in the altered variety.

GRANODIORITE OF ROCKING CHAIR LAKES

The Granodiorite of Rocking Chair Lakes was named by Johnson and others (1987) for dominantly granodioritic plutons which intrude the Volcanics of Silver Mine Lakes and Gabbro of Clark Creek. The intrusive contacts are often sheared and/or faulted. The Rhyolite Intrusive of Fire Center Mine is interpreted as a late-stage, more evolved equivalent of the granodiorite plutons (Baxter, 1988; Johnson others, 1987; Bornhorst and Baxter, 1987).

The Granodiorite of Rocking Chair Lakes is medium gray to light pink, medium to coarse grained, hypidiomorphic to allotriomorphic granular, and is composed dominantly of granodiorite with lesser tonalite, quartz monzonite, quartz monzodiorite, and quartz diorite (using a Streckeisen diagram). The massive granodiorite is composed of plagioclase, K-feldspar, quartz, amphibole, and minor sericite, epidote, chlorite, apatite, and carbonate. A more amphibole-rich granodiorite, owing its origin to the assimilation of amphibole from the mafic country rocks, is typically a darker gray in color and medium- to fine-grained. The altered variety is red to orange, fine- to medium-grained, and is cross-cut by stockwork quartz veins. The foliated variety, found along intrusive contacts, is a gray to black, fine-grained to aphanitic, schistose mylonite. The mineralogy of this variety consists of plagioclase, chlorite, K-feldspar, quartz, and minor apatite,

sericite, and epidote (Johnson and others, 1987).

STRUCTURE

The rocks in the northern part of the Marquette Greenstone Belt were affected by several deformational episodes in the Archean and Lower Proterozoic (Penokean). The first event folded, sheared, faulted, and metamorphosed the Archean rocks of the Marquette Greenstone Belt in Archean time. A later event folded, faulted, and metamorphosed the Lower Proterozoic sediments and diabase of the Marquette Range Supergroup and had a less definite effect on Archean rocks. Some minor reactivation of Archean faults may have taken place during the Penokean deformation. Distinguishing between Archean and Penokean metamorphism is difficult since they are both greenschist facies, but in the Island Lake Area where Archean metamorphism reaches amphibolite facies, Penokean metamorphism is denoted by retrograde assemblages and fabrics (Johnson and others, 1987).

Foliations in the region are defined by slaty, phyllonitic, and schistose cleavages and generally trend N70°W. These cleavages are most prominently displayed in the lepidoblastic textured, mafic rocks. Most foliations in the Archean rocks are interpreted to have been formed during the Late Archean tectonic event. The Archean rocks in the area of Silver Mine Lakes, Clark Creek, and Silver Creek lie on the southern limb of a steeply plunging, synformal anticline (Johnson and others, 1987). The nose of this regional fold is exposed to the northwest of Silver Creek where the hinge region of this structure has been intruded by the Granodiorite of Rocking Chair Lakes.

There are several generations of faults in the region that faults probably formed during various pulses of the Late Archean deformational event. The oldest faults in the area generally trend southeast-northwest to east-west, are generally ductile in nature, and would be termed shear zones in Ontario. A large structural zone, the Dead River Shear Zone, also trends southeast-northwest, and was initiated during the Archean. This zone is typified by steeply dipping, phyllonitic

to highly schistose volcanic rocks. It originated as an Archean ductile shear zone which subsequently had a minor portion reactivated as a relatively brittle fault during the Early Proterozoic.

Earlier Archean faults and shear zones are truncated, and locally offset by slightly younger, north-south to northeast-southwest trending Archean faults. The deformational regime for these faults was relatively brittle in contrast to the older ductile faults. It is likely that movement along these faults took place in the waning stages of the Archean deformational event because they offset the zone of highly altered basalts.

MINERALIZATION

Mineralization in the region exists in two forms: 1) disseminated sulfides within altered country rocks, and 2) quartz-carbonate-sulfide veins. Disseminated mineralization is most prominent in the highly altered variety of the Pillowed Basalt Member and in the Iron Formation Member, but also occurs occasionally in other Archean rock types. It consists of disseminated pyrite and sporadic minor pyrrhotite and chalcopyrite. The alteration minerals in the country rocks are primarily chlorite, sericite, carbonate, and quartz.

The veins of quartz and carbonate, and lesser amounts of chlorite, are often associated with shear zones and faults. The chief sulfide mineral is pyrite with much lesser amounts of chalcopyrite, arsenopyrite, and pyrrhotite. Locally, galena and sphalerite are the dominant sulfide vein minerals.

In general, it appears that two episodes of mineralization have affected the volcanics and intrusives of the northern part of the Marquette Greenstone Belt. The early episode produced the majority of the disseminated mineralization and was likely controlled by the location of the east-west trending faults and shear zones. This event was also responsible for the production of zones of intense carbonatization, sericitization, and chloritization. The second episode produced primarily carbonate-quartz veins with associated galena, sphalerite, and chalcopyrite

mineralization. These veins are localized near the areas of younger, north-south, brittle faults. Anomalous precious metal values can be found associated with both episodes of hydrothermal mineralization.

GEOLOGIC HISTORY

The earliest event in the region north of the Dead River Storage Basin was the extrusion of the sub-aqueous, tholeiitic, pillow basalts that form the Pillowed Basalt Member of the Volcanics of Silver Mine Lakes. The age of these basalts is about 2.7 Ga based on the radiometric age dating of a rhyolite intrusive which cuts basalt beneath the Clark Creek Basin (Trow, 1979). During eruption of the basalts, several thin mafic to intermediate volcanic mudflow breccias that contain locally abundant iron formation debris were deposited. Continued extrusion of subaqueous lava flows produced additional pillow basalts. The volcanic pile was then intruded by dikes and sills of gabbro (Gabbro of Clark Creek). The mafic rocks were synchronously deformed and intruded by syn- to post-tectonic rhyolite and granodiorite (2.7 Ga). The rhyolites may represent differentiated portions of the granodiorite plutons (Bornhorst and Baxter, 1987). An episode of syn- to post-tectonic hydrothermal alteration resulted in the precious metal mineralization. The Late Archean deformation and hydrothermal activity also produced the foliated and altered varieties of the Pillowed Basalt Member of the Volcanics of Silver Mine Lakes.

ACKNOWLEDGEMENTS

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Geology of the Ropes Gold Mine

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INTRODUCTION

The Ropes gold mine is located in the south-west part of the Archean Marquette Greenstone Belt, 5.8 km northwest of the town of Ishpeming, Michigan, at latitude 46° 32', longitude 87° 43', in the S1/2 NW1/4 Section 29, T48N, R27W, Ishpeming Township, Marquette County, Michigan, USA. The mine can be reached by traveling northward from US Hwy 41, west via paved County Road 573, then west via unpaved County Road GCL (the Ropes mine access road).

HISTORY

Julius Ropes, a druggist and prospector from Ishpeming, Michigan, discovered a gold-bearing quartz stringer in 1880 while prospecting for asbestos and serpentine "marble" in low ground near the east end of the present-day Ropes mine property. Continued prospecting resulted in discovery of the outcrop of the Ropes main ore zone approximately 250 m west of the initial discovery (Allen, 1912). The original Ropes mine operated sporadically from 1882 to 1897, producing 1029 Kg of Au and 2057 Kg of Ag from 195,000 tonnes of ore. The property remained idle, except for minor cyanidization of tailings, until Calumet and Hecla Consolidated Copper Co. conducted extensive surface and underground exploration from 1935 to 1942 and outlined 1,393,000 tonnes of ore averaging 3.98 g/tonne Au (Broderick, 1945). The relatively low grade of the deposit at a time of controlled gold prices, combined with wartime restrictions on precious metals mining, precluded any production at that time. Callahan Mining Corporation of Phoenix, Arizona, purchased the property from Arcadian Copper Mine Tours in 1975, began exploration in 1979, and made a decision to develop the mine in mid 1984. Production began in September 1985, and is now about 1,800 tonnes per day.

GEOLOGY OF THE SW PART OF THE MARQUETTE GREENSTONE BELT

Rocks in the southwest part of the Marquette Greenstone Belt, which host the Ropes mine, generally have mineral assemblages of the lower greenschist facies, except in proximity to the granitoid rocks which bound the greenstone belt, where amphibolite facies assemblages occur. The greenschist facies rocks are characterized by a sub-vertical planar foliation, defined by a weak parallelism of aphanitic phyllosilicate minerals, which is commonly conformable to flow margins in volcanic rocks, graded bedding in graywackes, and compositional layering in units such as chert-magnetite iron formation. There are relict cumulate textures in serpentinized peridotite, pillows in basalt, and bipyramidal and embayed quartz grains, and lithic fragments in volcanoclastic rocks. Therefore, rocks with readily recognizable primary structures and textures are referred to here in by their sedimentary or igneous names as recommended in the North American Code of Stratigraphic nomenclature; the prefix "meta-" is implied. Hydrothermally altered rocks in the immediate vicinity of the Ropes mine are referred to by their dominant mineral assemblages listed in decreasing order of abundance, such as "quartz-sericite-chlorite rock."

The southwest part of the greenstone belt comprises, from WNW to ESE, a sequence of: (1) pillowed to massive tholeiitic basalt, associated hypabyssal gabbroic sills and dikes, and subordinate mafic-volcanic derived graywackes; (2) an inter-layered zone of basalt, dacite tuff, and porphyritic dacite sills; (3) dacite tuff with subordinate tuff breccia, which hosts banded quartz-magnetite iron formation and quartzose graywacke immediately west of the Ropes mine; (4) serpentinized, fine grained peridotite, which is carbonatized and talc-altered in proximity to the Ropes mine; and (5) volcanic conglomerates and tuff breccias of dacitic composition. The volcanic units strike ENE, dip subvertically, and top consistently to the southeast, based on pillow facing directions and graded bedding (Callahan Mining Corporation detailed geologic mapping and drill core logs). The serpentinized peridotite has a relict, fine grained cumulate texture and was likely a hypabyssal

sill complex emplaced within the volcanic section, based on its fine grain size and local complex interlayering with the volcanic rocks. The rocks which most directly host the Ropes mine represent one of six known localities where volcanic rocks are interlayered with the serpentinized peridotite (Callahan Mining Corporation detailed geologic mapping and drill core logs); other volcanic inliers may exist in poorly to non outcropping low ground throughout the outcrop belt of the serpentinized peridotite.

The Ropes mine is located to the southeast of the basalt-to-dacite transition zone and the layers of banded iron formation and graywackes (Figure 1). The Ropes gold deposit is hosted by quartz-sericite-chlorite rock interpreted as hydrothermally altered dacite tuff on the basis of the progressive development of pervasive quartz and sericite alteration. This alteration gradationally replaces and finally totally pseudomorphs feldspar phenocrysts, matrix feldspar, and felsic lithic fragments in the tuffs as the Ropes mine is approached from the west. Similar less mobile trace element abundances and similar chondrite-normalized rare earth patterns between unaltered (except for greenschist facies metamorphism) dacite tuff to the west of the Ropes mine and the quartz-sericite-chlorite rock which hosts the Ropes deposit also provides evidence for a common origin (Callahan Mining Corp., unpublished data).

GEOLOGY OF THE MINE AREA

There are four main rock types within the immediate mine area: (1) Fine grained quartz-sericite-chlorite rock encloses the ore zones, strikes N70°E and dips steeply south. This rock type is bounded to the north and south by, (2) fine grained, carbonate-quartz-chlorite rock which is massive to compositionally layered on a scale of several millimeters. The quartz-sericite-chlorite rock and the carbonate-quartz-chlorite rock are locally complexly interlayered, particularly within and west of the mine (Figures 1, 2, 3). Contacts between the two rock types are generally sharp. The carbonate-quartz-chlorite rock is flanked

EXPLANATION FOR FIGURE 1



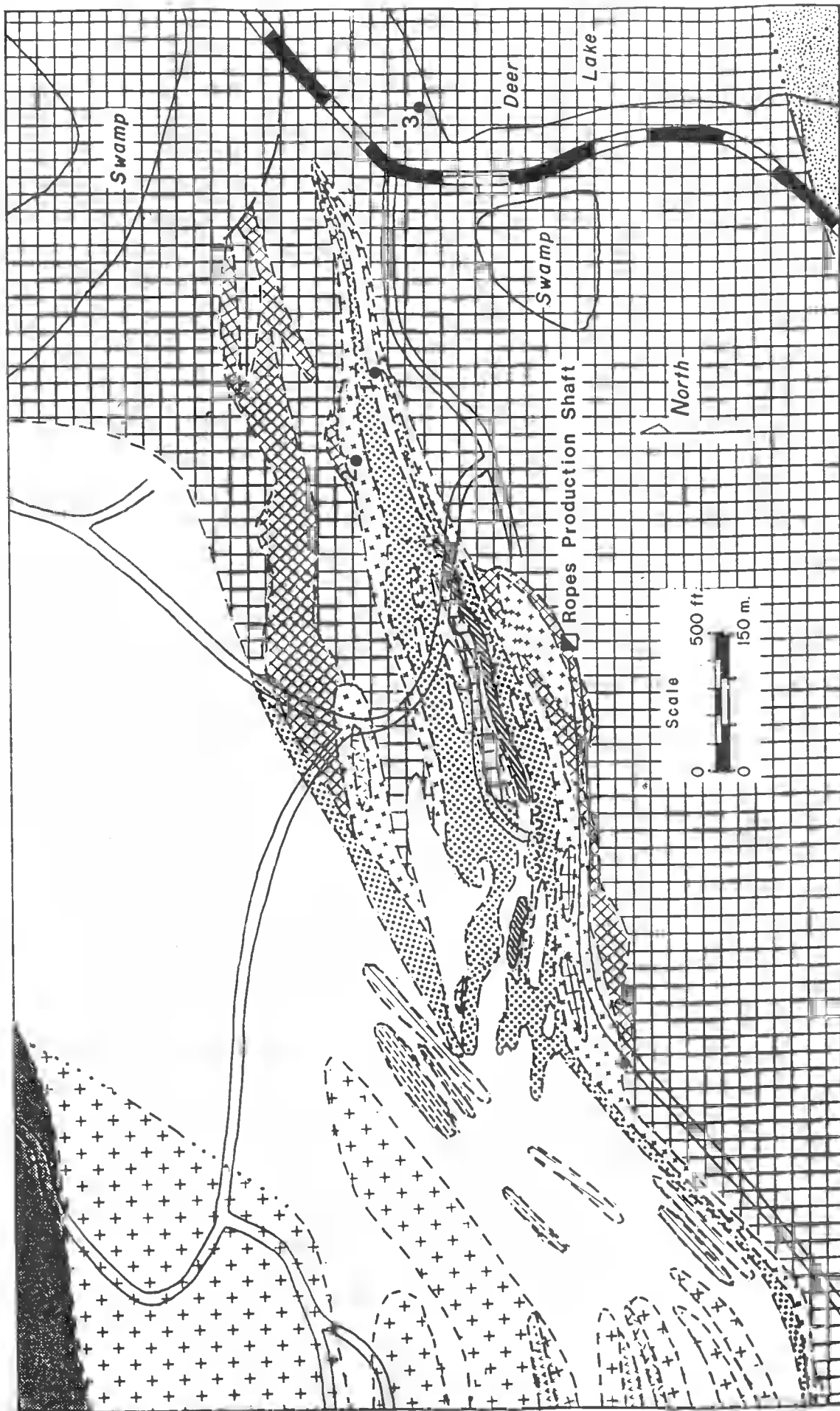


Figure 1. Geologic Map of the Ropes Mine area. Explanation on preceding page.

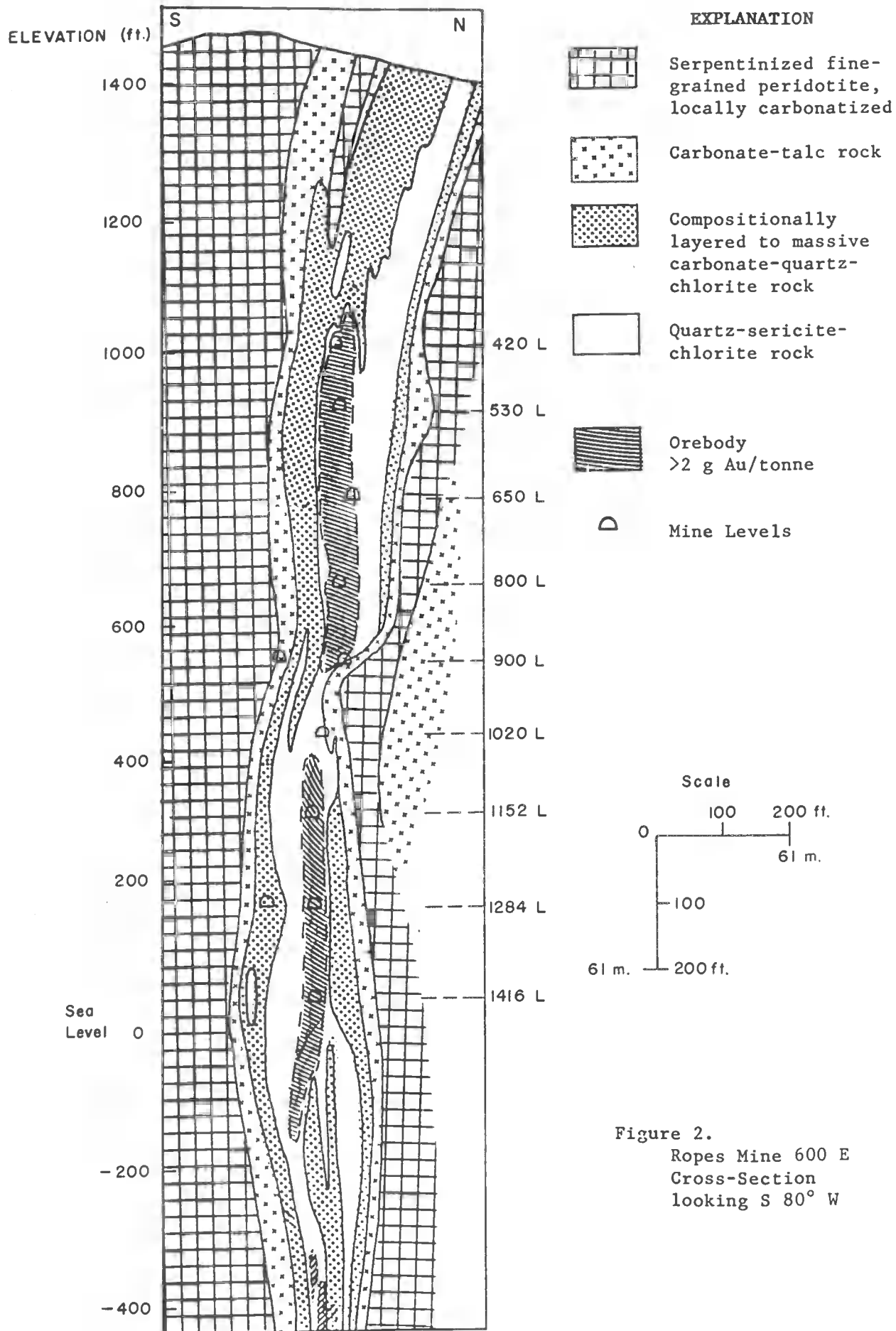


Figure 2.
Ropes Mine 600 E
Cross-Section
looking S 80° W

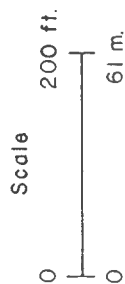
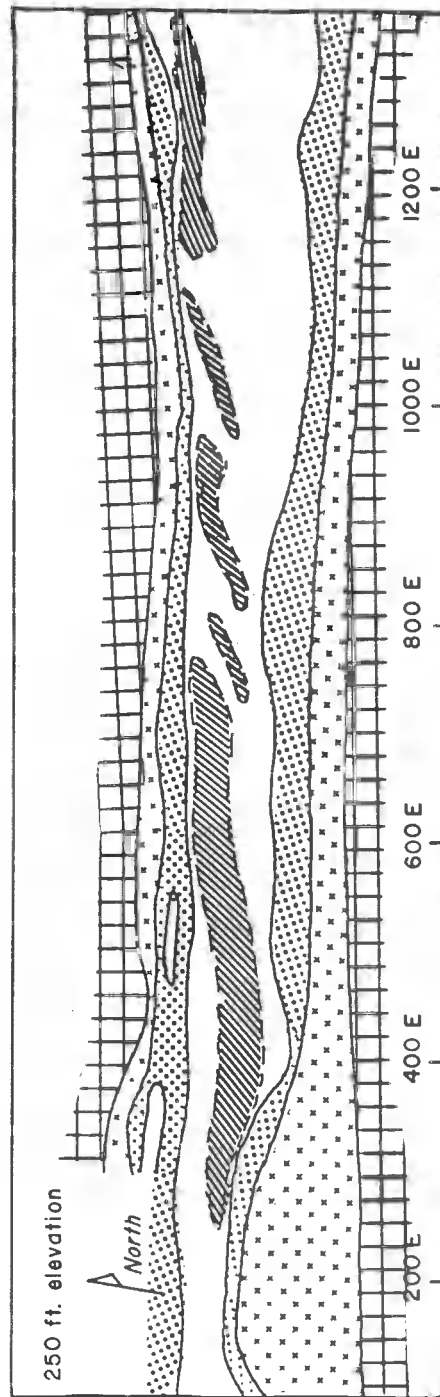
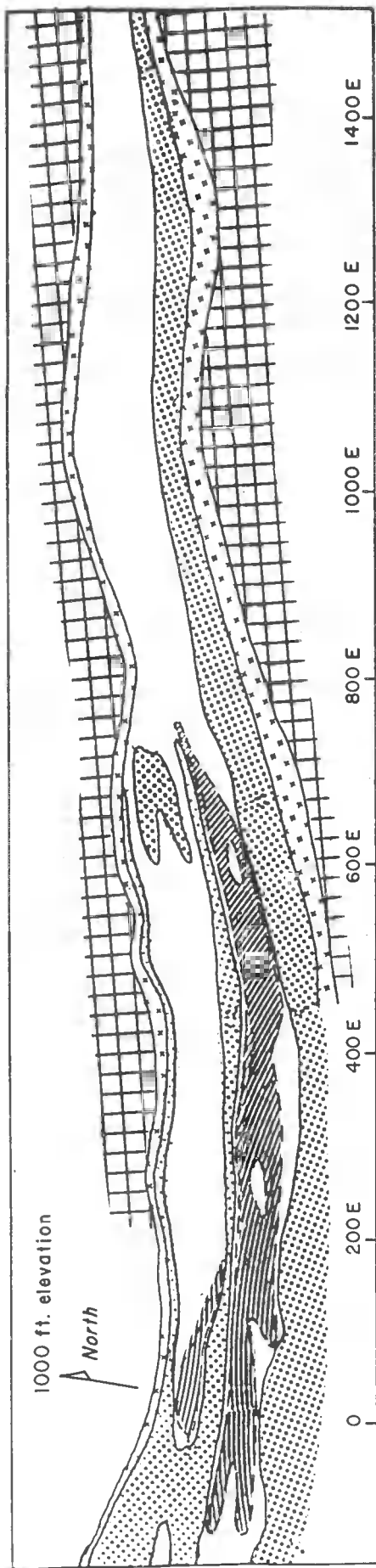


Figure 3. Geologic plan maps of the Ropes Mine.
See Fig. 2 for explanation.

successively, on both the north and south sides, by, (3) fine grained, massive to moderately foliated, carbonate-talc rock, and (4) fine grained, totally serpentinized peridotite which commonly retains a relict cumulate texture after original olivine and lesser pyroxene. This rock is carbonatized to varying degrees near its contacts with the carbonate-talc rock. Contacts between the carbonate-quartz-chlorite rock and the carbonate-talc rock, and between the carbonate-talc rock and the serpentinized peridotite are generally gradational over one to several meters.

The preservation of relict feldspar and lithic clasts, and the total thickness of quartz-sericite-chlorite rock, increases gradationally westward from the Ropes main ore zone (Figure 1) over a distance of several hundred meters into a large body of dacite that has moderately aligned twinned plagioclase phenocrysts, bipyramidal quartz, and volcanic rock fragments in an aphanitic quartz-sericite-feldspar-chlorite matrix characteristic of a crystal-lithic tuff. The dacite locally contains intervals of lapilli-sized fragments. The carbonate-quartz-chlorite rock is restricted largely to the mine area (Figure 1), although thin intervals up to 2 m thick occur up to 400 m west of the Ropes main ore zone. The thickest intervals of carbonate-talc rock occur within the mine area (Figure 1); however, thin intervals of talc-rich rock occur at numerous localities at the contacts of, and also in, serpentinized peridotite away from the mine area (Rossell, 1983). Serpentinized peridotite occurs up to 2 km northeast of the Ropes mine and up to 5 km southwest of the mine in a northeast trending set of outcrops, approximately 600 m wide (Clark et.al., 1975).

MAJOR ROCK TYPES IN THE ROPES MINE PROPERTY

Quartz-Sericite-Chlorite Rock

The main host for gold is light green, massive to slightly foliated, fine grained, quartz-sericite-chlorite rock with relict clasts. This rock is up to 40 m thick on the 800 Mine Level, but narrows toward the surface and toward the east to less than 6 m thick. It is complexly interlayered with carbonate-quartz-chlorite

rock, especially west of the Ropes main ore zone (Figure 1) and in the mine (Figures 2 and 3). The rock has equant quartz grains 50 to 100 microns in diameter in a randomly oriented to moderately aligned sub-20 micron quartz, sericite, and minor chlorite matrix. Randomly oriented to moderately aligned, 1 to 2 mm, angular, rectangular mats of sub-10 micron sericite and minor quartz are enveloped in this matrix and have an external habit very much like the plagioclase phenocrysts in the thicker, more massive, lateral equivalent of this rock immediately west of the mine. This textural change is gradational eastward toward the orebody over a distance of a few hundred meters and is characterized by increasing alteration of the plagioclase phenocrysts to sericite and an increase in the abundance of quartz and sericite in the matrix, with a corresponding decrease in feldspar. Therefore, the sericite-rich mats in the quartz-sericite-chlorite rock of the mine are interpreted as pseudomorphs after plagioclase phenocrysts. The sericite pseudomorphs constitute up to 20 percent of the rock. Uncommon clasts, 1 to 2 mm in diameter and composed of microcrystalline aggregates of quartz, may represent pseudomorphs of quartz phenocrysts which now exhibit subgrain development, or alternatively, some may be chert fragments. Chlorite-quartz fragments, which may be more mafic volcanic rock fragments or pseudomorphed mafic mineral phenocrysts, occur less commonly in the rock. Chlorite is generally a subordinate component of the rock at less than 10% and occurs both dispersed in the matrix and locally as coarser laths which define a slight foliation. Ferroan dolomite is locally a minor component of the matrix. The rock is layered locally with 5 mm thick, planar, sericite-rich and alternate more chlorite-rich laminae.

Gold abundance is generally greatest where very fine to aphanitic pyrite comprises 5 to 8% of the rock, quartz and sericite are most abundant, and chlorite is least abundant (this generality does not apply in the case of the chloritic, pyritic, farthest eastern rim of the Ropes main ore zone, as discussed in the subsequent section on "The Orebodies"). Rock with greatest gold abundance

contains only trace amounts of carbonate, compared with higher but still minor concentrations of carbonate in less auriferous parts of the quartz-sericite-chlorite rock. Fine pyrite, 50 to 100 microns in diameter, is dispersed in the rock matrix and less commonly within the sericite pseudomorphs after plagioclase and is not confined only to quartz veinlets or to foliation planes. Coarser pyrite, 0.5 to 1 mm in diameter, occurs near quartz veinlets and also along chloritic foliations. This relatively coarse pyrite is enclosed locally by quartz over-growths, and is occasionally pulled apart along the foliation. Rock characterized by only coarser pyrite is not ore. Quartz veinlets less than 1 mm thick comprise up to several percent of the rock and are randomly oriented. Quartz in the veinlets commonly has undulatory extinction and local mortar texture. Rock outside of the ore zones is characterized by <2% very fine pyrite.

Carbonate-Quartz-Chlorite Rock

Carbonate-quartz-chlorite rock envelopes the afore-mentioned quartz-sericite-chlorite rock and is complexly interlayered with it, particularly toward the west end of the Ropes mine (Figure 1). The carbonate-quartz-chlorite rock contains abundant ferroan dolomite, and lesser quartz and chlorite. Minor sericite occurs in some specimens, and minor talc in others, but these two minerals are generally mutually exclusive. Contacts with the quartz-sericite-chlorite rock are sharp; however, minor carbonate minerals are present in the quartz-sericite-chlorite rock near its contacts with the carbonate-quartz-chlorite rock, and minor sericite is present in the carbonate-quartz-chlorite rock near its contacts with the quartz-sericite-chlorite rock. Typically, this rock contains up to 150 ppb Au. Quartz-rich parts of the carbonate-quartz-chlorite rock are locally slightly pyritic and contain up to 1 ppm Au.

The carbonate-quartz-chlorite rock is commonly compositionally layered on a scale of several millimeters, but locally is massive. Layering is defined by parallel, fine to medium grained, white carbonate laminae, chlorite foliation, and

quartz-chlorite-rich laminae. The rock is increasingly talcose toward the contact with carbonate-talc rock. Coarse grained, barren, white dolomite veins up to 5 cm thick cut across all other features and comprise <1% of the rock. Carbonate-quartz-chlorite rock occurs not only in the mine, but also in a layer up to 60 m thick on the north side of the mine (Figure 1), where it contains thin layers of the other three main rock types.

Serpentinized Peridotite and Carbonate-Talc Rock

The interlayered quartz-sericite-chlorite rock and carbonate-quartz-chlorite rock are bounded on the north and south by sill-like masses of serpentinized peridotite. There are several smaller serpentinized peridotite bodies within the carbonate-quartz-chlorite rock on the north side of the Ropes mine. The larger of these minor serpentinized peridotite masses forms the north wall of the Ropes mine (Figures 1, 2). The rock is dark gray to green, fine grained serpentine containing lesser talc and carbonate, and minor chlorite, with accessory chromite and magnetite. Commonly it has a relict cumulate texture of 1 to 3 mm serpentine pseudomorphs after olivine and pyroxene, which are surrounded by rims of talc and carbonate, although locally the rock is dark green, felted textured serpentine. The serpentinized peridotite is increasingly carbonate-rich toward its borders, although relict texture is commonly continuously preserved. Au abundance is typically less than 30 ppb in the serpentinized peridotite, even in close proximity to the mine.

Massive to well foliated, gray to dark green, very fine grained carbonate-talc rock occurs around the margins of serpentinized peridotite (Figures 1, 2, 3). The carbonate-talc rock has gradational contacts over one to several meters with serpentinized peridotite and with talc-rich parts of the carbonate-quartz-chlorite rock. The carbonate mineral in the carbonate-talc rock is dominantly ferroan dolomite with minor magnesite. Au abundance ranges from <30 ppb to approximately 100 ppb in the carbonate-talc rock.

The spatial association of carbonate-talc rock with the margins of serpentinitized peridotite, the gradational contacts with serpentinitized peridotite, and the similar less mobile trace element composition of the carbonate-talc rock and serpentinitized peridotite, especially with regard to Cr content, suggests that the carbonate-talc rock is the altered margins of serpentinitized peridotite masses.

SUMMARY OF MINERAL COMPOSITION

Minerals in rock samples from selected traverses across and along the strike of the Ropes deposit were analyzed by electron microprobe. Although detailed mineral chemistry is not dealt with here, a brief summary of general trends is included in this field guide (Callahan Mining Corporation, unpublished data).

Chlorite occurs in nearly all rock types, but its composition and abundance are variable. In general, the Fe/Mg ratio of chlorite increases toward the center of the quartz-sericite-chlorite rock and away from serpentinitized peridotite. The chlorite is mostly sheridanite in the quartz-sericite-chlorite rocks and clinocllore in the other major rock types.

Talc increases in iron content from serpentinitized peridotite toward quartz-sericite-chlorite rock, but is absent in the quartz-sericite-chlorite rock itself. Talc compositions show a narrow range, with an $\text{Fe}/(\text{Fe}+\text{Mg})$ cation ratio between 0.0 and 0.11, centered at 0.05.

Sericite is restricted mostly to the quartz-sericite-chlorite rock and is minor in carbonate-quartz-chlorite rock, where these two rocks are in contact. The sericite is an Fe- and Mg-bearing muscovite, with FeO and MgO contents of as much as several wt.% each. The sum of Mg+Fe cations in the sericite structural formula, on the basis of 22 oxygens, is between 0.4 and 1.2 cations, centered at 0.6 cations. No consistent trends in sericite composition were recognized in the rocks of the Ropes mine.

Carbonate minerals are common to all rocks and are dominantly low iron dolomite and lesser pure dolomite. Low iron dolomite is a minor component in

quartz-sericite-chlorite rock, but is a major component in the other three major rock types at the Ropes mine. Calcite is minor in quartz-sericite-chlorite rock. Magnesite is commonly a major component of the serpentinized peridotite and the carbonate-talc rock. Serpentine is major in the serpentinized peridotite. Disseminated chromite is minor in the serpentinized peridotite and carbonate-talc rock.

The differences in mineral composition probably reflect, in large part, original differences in bulk composition between serpentinized peridotite and the dacitic volcanoclastic protolith of the quartz-sericite-chlorite rock. Talc and chlorite compositions are more Mg-rich, and Mg-carbonate minerals are also more abundant toward the serpentinized peridotite.

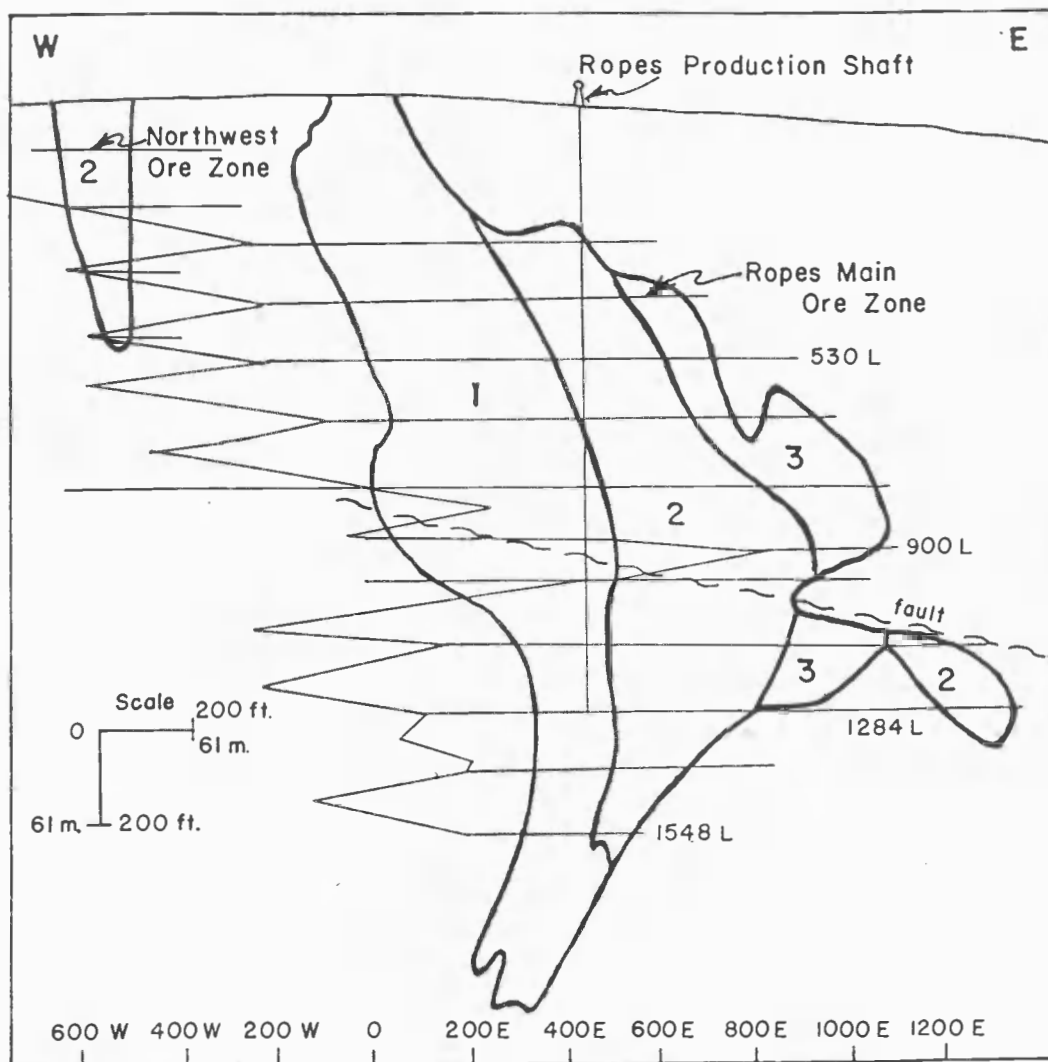
STRUCTURE

The dominant structural element in the Ropes mine area is a N70°E sub-vertical foliation defined by the alignment of aphanitic phyllosilicate minerals, which is generally parallel to the layering between rock types. The overall strike of the Ropes main ore zone also nearly parallels this foliation. A slight, sporadically present sub-vertical second foliation strikes N45°E and is defined by generally slightly coarser grained phyllosilicate laths.

Several ore-related structural elements characterize the Ropes deposit: 1) a series of N55°E to N65°E striking, vertically dipping, steeply westward plunging, auriferous quartz vein-dominated pods occur progressively further east in successively deeper levels of the mine. These pods occur at, or south of, the south side of the Ropes main ore zone; 2) cryptic zones of significantly higher grade Au mineralization, defined solely on the basis of assay data, are contained more centrally within the Ropes main ore zone. The middle parts of these higher grade zones strike across the overall N80°E trend of the orebody in en-echelon fashion at approximately N55°E, while the extremities of these higher grade transverse zones have a nearly N70°E trend, thus forming a low angle sigmoidal

pattern across the ore zone (Figure 5). This pattern can best be recognized at the 250 ft. elevation in the mine, toward the east end of the Ropes main ore zone (Figure 3).

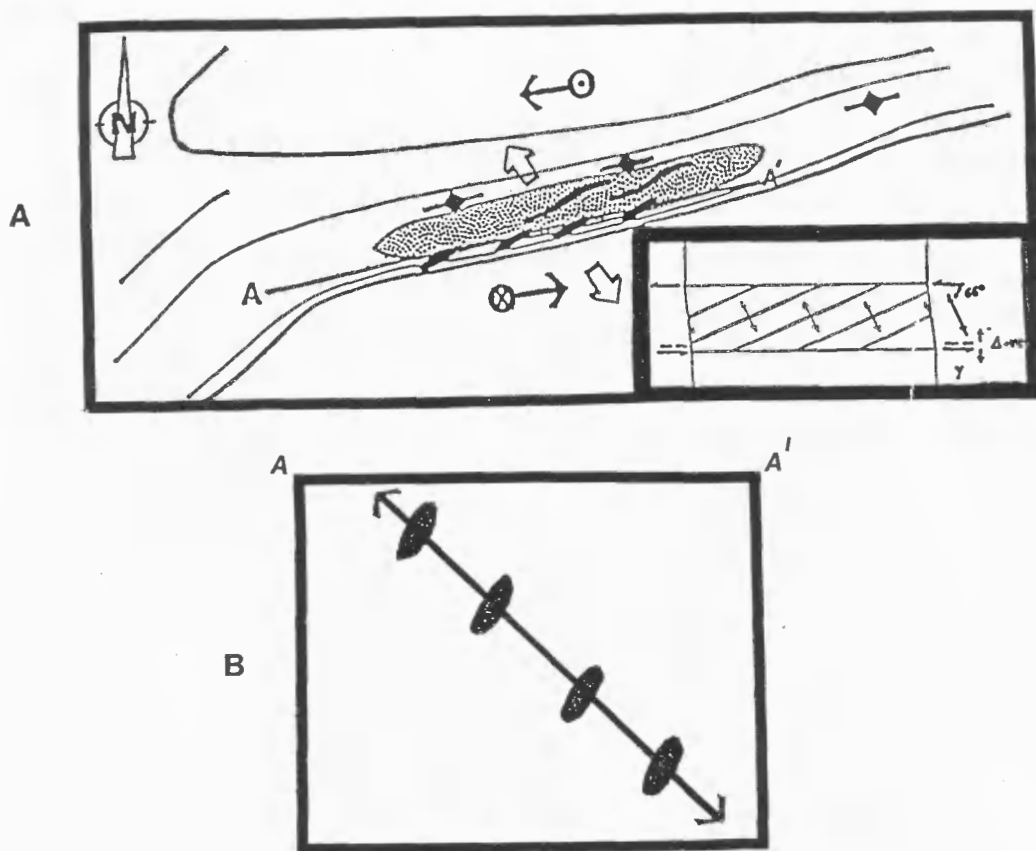
Both of the above structural elements can be regarded as extensional features. The quartz vein dominated pods are evidence of silica addition in incipient voids. The higher grade transverse zones within the main ore zone, while not strictly veins, nonetheless may have been zones of increased permeability to ore fluids. A comparison with shear zone models presented in Ramsay and Huber (1983) demonstrates that the above structural elements are best interpreted as extensional features, and that the rocks containing the Ropes deposit can be considered to represent a structural setting involving some degree of simple shear, with a component of positive volume change in the shear zone. Figure 5 compares the theoretical orientation of extensional vein arrays developed in a shear zone as a result of positive volume change in a shear zone with the observed geologic relations of ore related structural elements at the Ropes mine: it is geometrically correct that en-echelon fissure systems will always make angles of less than 45° to the trend of the shear zone in cases where positive volume change is involved (ibid). The observed geometric relationships at the Ropes mine between the two ore related structural elements discussed above, and the shear zone "walls" (the nonfoliated serpentized peridotite), are consistent with the required acute angle relationship. The required relative sense of shear in the present day horizontal plan view of the Ropes mine area is, therefore, north side to the WSW and south side to the ENE, as illustrated in Figure 5. Connecting the midpoints of the quartz vein dominated pods at the Ropes mine gives the true sense of shear in the third dimension as lying along a line oriented down to the ENE and up to the WSW (Figure 5). A simultaneous consideration of the plan and long section views necessitate that the south side of the zone had an ENE and downward net component of movement, while the north side of the zone had a WSW and upward net component of movement.



Major Gold Ore Types

1. Light green to tan quartz-sericite rock, with lenses of light gray cherty quartz rock containing pyrite-tetrahedrite-chalcopyrite-galena. Pyrite content of this ore type does not correlate with gold grade
2. Light green quartz-sericite-chlorite-pyrite rock. Good correlation between fine-grained pyrite content and Au grade.
3. Dark green quartz-chlorite-pyrite rock. Consistently high fine-grained pyrite content and high gold grade.

Figure 4. Ropes Mine long-section looking N 10° W



EXPLANATION:

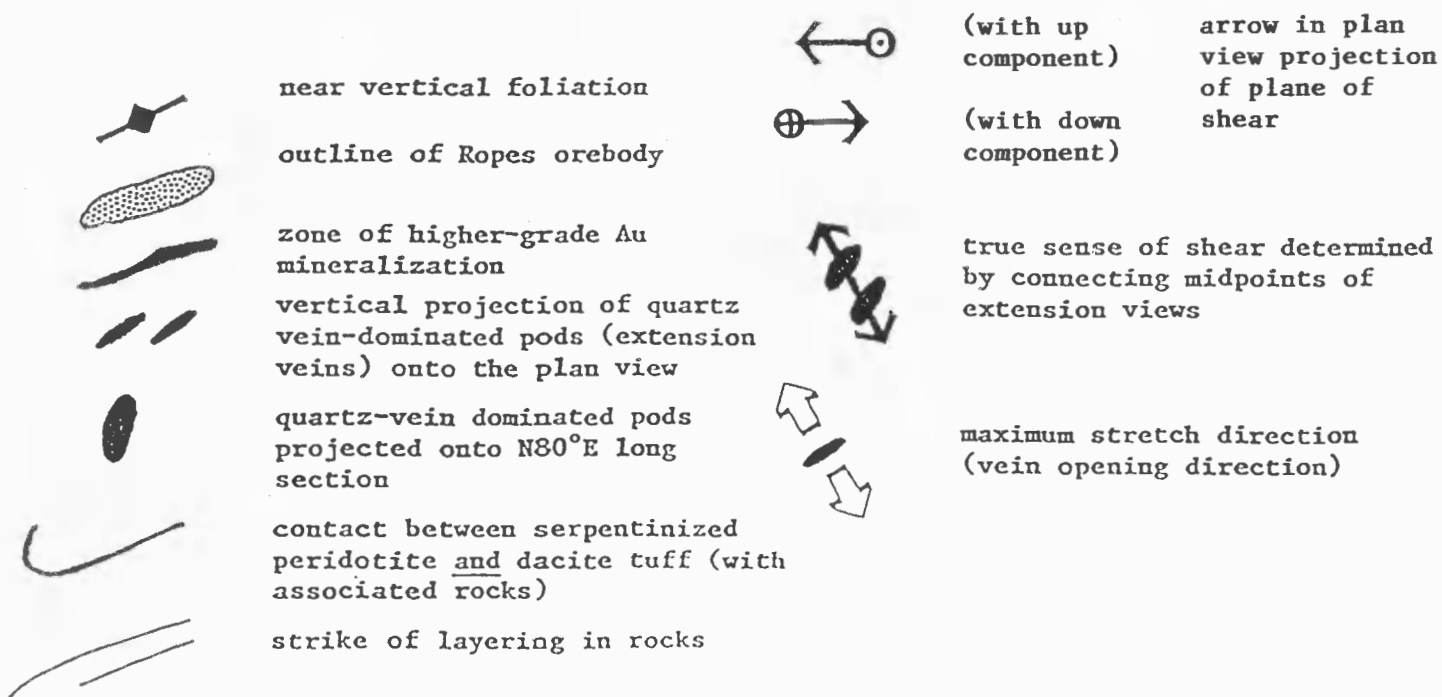


Figure 5: Schematic structural diagrams of the Ropes Mine
A is plan view, inset after Ramsay and Huber, 1983, Figure 3.21A; B is N80°E vertical long section view

THE OREBODIES

The Ropes mine main ore zone is steeply dipping, 335 m in maximum strike length, 12 m in average thickness, and 600 m in presently defined down-dip extent (Figure 4). It occurs within the quartz-sericite-chlorite rock, and is characterized by disseminated pyrite with only minor quartz veins. The total stated property tonnage, including historic production through 1987 and geologic reserves, is approximately 2.5 million tonnes at 3.25 g/tonne Au. Based on available information from the upper third of the Ropes main zone, the Ag grade is estimated at 12 g/tonne.

The Ropes main ore zone can be divided longitudinally into three major ore types based on the physical characteristics of the ore, as illustrated in Figure 4. In plan view, these ore types form crescent-shaped, concentric shells, with the convex side of each ore type toward the east and the concave side toward the west. The convex-to-the-east geometry of the ore type zones, along with an overall gradual western cutoff of Au mineralization and a sharp eastern cutoff, suggests that the flow vector for the mineralizing fluids, relative to the present-day surface, may have been upwards from the deep, southwest end of the deposit toward the shallower northeast, high grade keel of the deposit.

The Ropes main ore zone is cut by an east-striking, south-dipping, low angle reverse fault zone at the 900 mine level (Figure 2). Offset of units across the fault zone is generally greater at the south side of the mine than at the north side. The orebody thins down dip toward the fault zone, but thickens below it.

Several other gold-mineralized bodies exist on the Ropes property. The Northwest ore zone is a small ore zone to the northwest of the Ropes main ore zone (Figure 4). Significant intersections of gold-mineralized rock, comparable in grade and width to the Ropes main ore zone, have been encountered in deep drilling 370 m below the Ropes mine 1284 level (Callahan Mining Corporation news release, July 20, 1987).

In general, most gold occurs associated with sub-100 micron sized pyrite

which is dispersed throughout the mass of the quartz-sericite-chlorite rock, as well as on fractures, foliations, and along quartz veinlets. However, in certain ore types the modal abundance of pyrite does not show a strict correlation with gold grade (see explanation, Figure 4). Native gold, of variable fineness, occurs as approximately 3 to 10 micron sized grains in the following specific sites: 1) attached to the surface of the fine grained pyrite, 2) included as fine blebs within the fine grained pyrite, 3) on fractures within the fine grained pyrite, and 4) at grain boundaries of fine grained quartz and sericite. A volumetrically minor amount of coarse free gold occurs on fractures in quartz stringers and lenses. Silver occurs as electrum, native silver, argentiferous tetrahedrite, argentiferous galena, and rare dyscrasite.

Pyrite comprises over 95% of the metallic minerals in the flotation mill concentrate, followed by chalcopyrite at 1%. Argentiferous galena, argentiferous tetrahedrite, sphalerite, hematite, magnetite, and rutile are present in trace amounts.

Fine grained, white to light gray sugary-textured auriferous quartz veins are concentrated at and south of the extreme south side of the Ropes main ore zone. Individual quartz veins are rarely up to a meter thick, but collectively these veins, interlayered with quartz-sericite-chlorite rock, form pods up to a maximum of 8 m thick and 30 m in strike and plunge extent. The pods strike approximately N65°E, compared to the N80°E overall trend of the Ropes main ore zone, plunge steeply to the west, and occur progressively further east at deeper levels of the Ropes mine, as discussed in the section on "Structure".

Accessory minerals in these quartz pods include: pyrite, minor argentiferous tetrahedrite galena, and chalcopyrite, and rare free gold, molybdenite, and dyscrasite. Trace tourmaline and native Ag were reported by Broderick (1945). These pods typically contain 4 to 7 g/tonne Au and approximately 20 g/tonne Ag. Although these pods are higher than average grade ore, the higher grade parts of the quartz-sericite-chlorite rock ore of the Ropes main ore zone are not zoned

about the pods; rather, the higher grade parts of the main ore zone, characterized by dispersed pyrite, occur more centrally within the trend of quartz-sericite-chlorite rock. It is estimated that the existing and mined out pods constitute, in total, approximately 5% of the ore at the Ropes mine.

DISCUSSION

The serpentinized peridotite bodies have contact relations with the bordering and interlayered volcanic rocks, as well as internal relict fine grained igneous texture, consistent with their intrusion as hypabyssal sills. Serpentinization preserved igneous textures, and was most likely at near constant volume (Best, 1982). This constant volume serpentinization process would have necessarily released large amounts of MgO and SiO₂ to the surrounding rocks (ibid). The voluminous carbonate-quartz-chlorite rocks, which bound and are interlayered with the Ropes gold deposit, are comprised primarily of weakly ferroan dolomite and lesser quartz. Their origin could conceivably be attributed to such a release of MgO and SiO₂ during serpentinization of the peridotite enclosing the trend of volcanic rocks at the Ropes mine.

The Ropes orebodies are overall tabular, stratiform and stratabound alteration zones in quartz-sericite-chlorite rock interpreted as dacite tuff on the basis of relict fragmental crystal-lithic textures preserved in and near ore. These pseudomorphs are clearly gradational to feldspar phenocrysts and lithic fragments in tuffs west of the Ropes mine. Additionally, the mine rocks have abundances of less mobile trace elements indicative of a dacitic composition. Gold mineralization at the Ropes mine is restricted to these rocks, and it appears that these originally feldspar-rich rocks provided a chemically receptive host for K₂O and Au bearing solutions, which altered the feldspar to sericite. Possibly, either better permeability in the tuffs relative to the dense crystalline peridotite, or else a ductility contrast between the volcanic rocks and peridotite, facilitated preferential focussing of ore bearing solutions. The bounding peridotite near the

mine is extensively carbonatized and appears to have been a sink for CO₂, possibly contained in the same Au-bearing solutions.

Certain ore-related structural elements such as a series of quartz vein dominated pods south of the Ropes main ore zone, and transverse zones of higher gold grade in the Ropes main ore zone, have geometric relations consistent with an origin as extensional features in a shear zone with positive volume change. Structural elements indicate that the net component of movement during some stage of gold mineralization was north side up to the WSW and south side down to the ENE, relative to the present-day ground surface. Furthermore, the overall concentric, convex to the east geometries of the major ore types in the Ropes main ore zone, combined with the gradual western cutoff of gold mineralization and sharp eastern cutoff in front of the high grade eastern "keel" of the deposit, suggests that the flow vector for mineralizing fluids, relative to the present day surface, may have been upwards from the deep southwest part of the deposit toward the shallow eastern high grade edge.

Timing of gold mineralization can be demonstrated as being later than deposition of the volcanic rocks which host the Ropes deposit, because alteration associated with the Ropes deposit affects the serpentized peridotite, which, on the basis of relict fine grained igneous texture and interlayering with the volcanic rocks, appears to be a hypabyssal sill complex, and, therefore, intrusive into the volcanic section. Emplacement of the peridotite may have been preferentially controlled by an early-formed structure which appears to have exerted a control on the original distribution of volcanic and sedimentary units: the peridotite occurs at or near a major, partially interlayered transition between basalt and dacite pyroclastic rocks. This transition is accompanied by a zone of sedimentary units including banded iron formation and quartzose graywackes. This major transition in the volcanic section, accompanied by sediments, could represent a break or zone of flexure which controlled the position of the interface between the two partly contemporaneous major volcanic facies. Such a boundary between contrasting

volcanic facies may have been controlled by a zone of crustal weakness which facilitated intrusion of upper mantle derived peridotite, as well as provided a conduit for focussing gold bearing solutions. The trend of volcanic rock which hosts the Ropes deposit is near this transition, and strikes away from the transition at an acute angle. The Ropes environment may represent a splay or second order structure off the more major break. The observed zoning of ore types at the Ropes mine, as discussed previously, is consistent with fluid flow from the direction of the inferred major break to the west of the Ropes mine, toward the present-day ENE. Persistent or recurrent movement along the inferred major structure which controls the distribution of major volcanic facies, could have provided a seismic pumping action to assist in moving large volumes of mineralized hydrothermal fluid. Such movement could also account for the ore related structural elements observed in the Ropes main ore zone, which indicate relative movement during at least part of the gold mineralizing process.

CONCLUSIONS

Gold mineralization at the Ropes mine occurs primarily with fine grained pyrite dispersed in quartz-sericite-chlorite rock interpreted as altered dacite tuff. The Ropes environment may represent a splay off a more major early formed structure which controls the distribution of the two major volcanic facies: basalt and dacite pyroclastics. The serpentinized peridotite, as well as gold bearing solutions, may have used this structure as a conduit.

ACKNOWLEDGEMENTS

The author thanks Glen Scott, Ropes mine Chief Geologist, who was instrumental in defining mappable units and compiling much of the geology at the Ropes mine. This paper benefited from editing and revision by Klaus Schulz, U.S. Geological Survey.

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Geological Field Trip to the Marquette Greenstone Belt: Part I
Day 1 Road Log - Stops 1 to 11

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NOTE: Additional information on the geologic setting of the field trip stops may be found in papers by Bornhorst and by Baxter & MacLellan in this volume.

Refer to Figure 1: **Route and Stop Map**

Mileage

0.0 Start Day 1 - Ramada Inn, Marquette

Assemble at the entrance of the Ramada Inn. From the Ramada Inn turn right (west) to Washington Street and proceed toward junction with U.S. 41. At 1.3 mi, turn right (west) to U.S. 41 and proceed toward Negaunee. At 6.4 mi, pull off to the right shoulder alongside of outcrops.

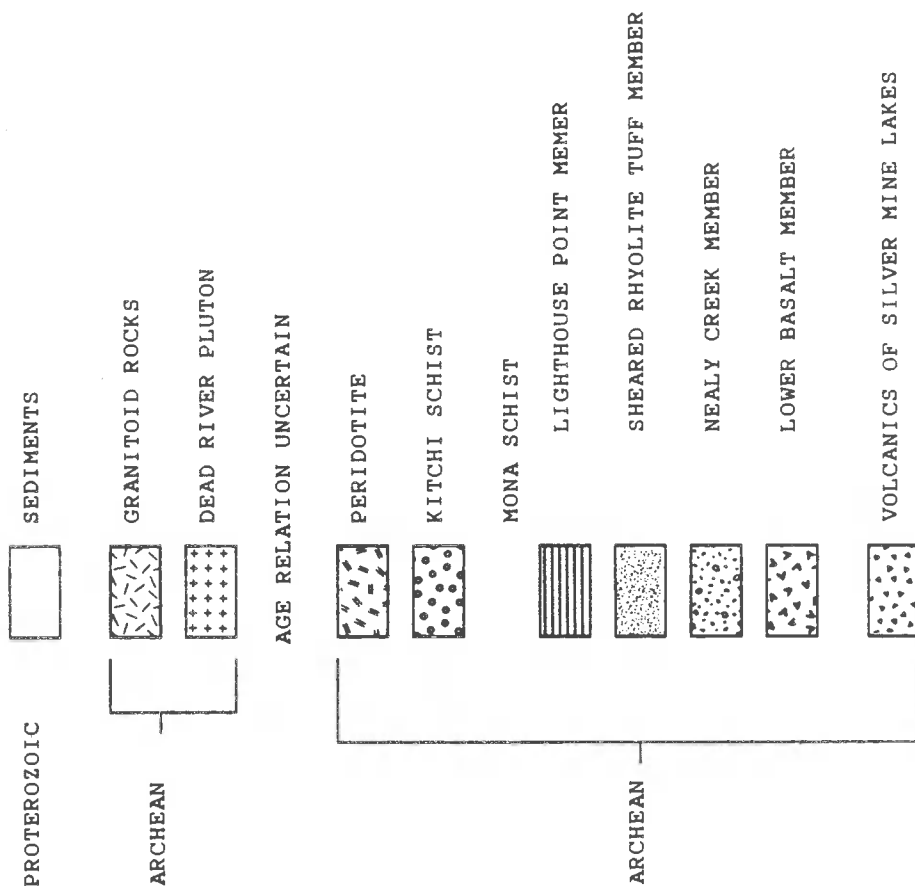
6.4 Stop 1 - Pillowed Basalt

The dominant volcanic lithologies in the Marquette Greenstone Belt are massive and pillowed tholeiitic basalt, the massive variety appearing to be more abundant perhaps because typical mossy outcrops may obscure the pillows. At this stop are excellent three dimensional views of relatively undeformed pillowed basalt. The pillows are ellipsoidal in shape with dimensions around 1' X 4' X 5'; attitude of bedding strikes approximately E-W and dips 85°N. Cusps on pillows indicate that here stratigraphic top is to the north. There are also characteristic radial fractures and interpillow void spaces filled with quartz and carbonate.

This locality was mapped most recently by Puffett (1974) as Lower Member of the Mona Schist. Location: NW¼, section 20, T48N, R26W.

Continue west on U.S. 41. At 7.6 mi, pass the road to Marquette County Airport. At 8.6 mi, large outcrop on opposite side of highway (south) is Stop 2 (for safety proceed 0.1 mi west, make a U-turn just before the Carp River, and proceed east to outcrop; when finished proceed east 0.05 mi, make a U-turn to U.S. 41 west).

LEGEND



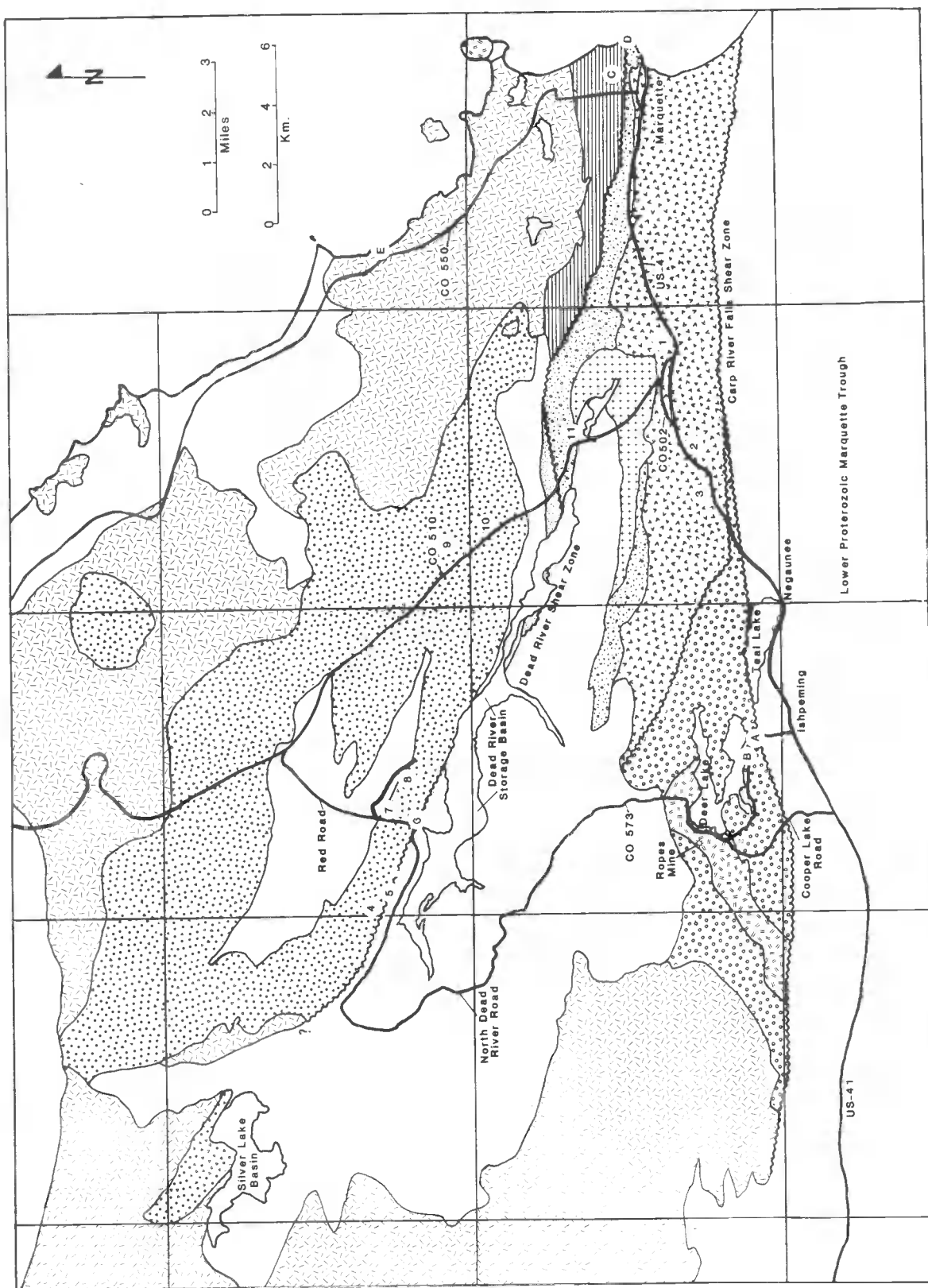


Figure 1: Route and Stop Map, Marquette Greenstone Belt, Michigan.

8.6 Stop 2 - Slightly Deformed Pillowed Basalt

The vertical road cut consists of slightly deformed pillowed basalt. Pillow rinds are not easily visible in the vertical face but are more conspicuous on the glacially polished surface on the top of the outcrop. Pillows are flattened and rinds have feathered edges; bedding strikes roughly E-W. Foliation strikes N86°W and dips 84°S. Quartz and carbonate veins containing a few percent euhedral pyrite parallel this foliation. Flat-lying fractures are filled dominantly with carbonate.

This locality was mapped most recently by Puffett (1974) as the Lower Member of the Mona Schist. Location: SW¼, section 28, T48N, R26W.

Proceed west on U.S. 41 and at 8.75 mi cross bridge over Carp River. At 9.3 mi, pull off to the right shoulder alongside a number of small outcrops.

9.3 Stop 3 - Deformed Archean Volcanic Rocks

The rocks in this road cut have a well-developed close-spaced foliation (N75-88°W, dip 70-89°S) which produces a slate-like appearance. These rocks are within the Archean Carp River Falls Shear Zone. There are two lithologies in this outcrop: chlorite schist from a basaltic parent, and quartz-sericite schist from a rhyolitic parent. The quartz-sericite schist is a tabular shaped body near the center of the outcrop, and is probably a dike based on analogous lithologies to the north. Near the extreme eastern end of the outcrop are probable pillow rinds which suggest the basalt parentage of the chlorite schist. Flat-lying fractures, similar to Stop 2, are present in the basalts but not in the rhyolites.

This locality was mapped most recently by Puffett (1974) as Undifferentiated Greenstone. Location: S½, section 29, T48N, R26W.

Proceed west on U.S. 41. At 10.2 mi, enter City of Negaunee and continue through Negaunee on U.S. 41 and towards Ishpeming. At 13.8 mi, traffic light at junction of County Road 573 and U.S. 41, turn right (north) to County Road 573. At 14.2 mi, pass cemetery on left, stay on main road, now called Deer Lake Avenue. At 14.9 mi, Deer Lake is visible on right, continue ahead on main road. At 16.7 mi, junction of County Road 573 with Cooper Lake Road on left, stay on 573. At 17.5 mi, gravel road to the Ropes Mine on the left (the field trip will

stop at Ropes on Day 2), continue on 573. At 22.4 mi, at Y-intersection, go left to the North Dead River Road; road turns to gravel at this point. At 27.7 mi, the hills on the right are Archean rocks of the Clark Creek area. At 28.8 mi, cross bridge over the Dead River; Archean rocks of the Silver Creek area are exposed in the steep topography ahead. At 28.95 mi, intersection of North Dead River Road and Silver Lake Road, proceed right (east) on North Dead River Road. At 30.2 mi, outcrops of Michigamme Formation in roadbed. At 30.8 mi, cross over Silver Creek, At 31.1 mi, turn left to dirt road towards Grigg hunting camp. At 31.4 mi, park at hunting camp and walk about 400 feet N20-25°E from the cabin to the Silver Creek prospect located on the side of the valley.

31.4 Stop 4 - Silver Creek Prospect

The Silver Creek Prospect consists of several shallow shafts and trenches. The prospect is dominated by a quartz and carbonate vein (up to 4 ft thick) which contains galena and sphalerite as the major sulfides, lesser amounts of pyrite and chalcopryrite, and trace amounts of arsenopyrite and pyrrhotite. Pyrite replaces pyrrhotite. A mineral separate of galena contained 120 ppm Ag and one of sphalerite contained less than 1 ppm Ag. A yellow sulfide separate (chalcopryrite, pyrite and pyrrhotite) contained 180 ppb Au. A grab sample of white massive quartz vein from the rock piles at this prospect contained 38 ppb Au and 4 ppm Ag. The vein is hosted by altered pillow basalt.

This locality was mapped most recently by Johnson and others (1987) and is designated as the Highly Altered Variety of the Pillowed Basalt Member of the Volcanics of Silver Mine Lakes. Location: NE $\frac{1}{4}$, section 25, T49N, R28W.

Proceed back to North Dead River Road and turn left (east) at 31.5 mi. At 31.8 mi, turn left and proceed to dirt logging road, turn right and follow logging road north, 0.05mi. At 32.1 mi, park, continue walking on dirt road about 950 feet (generally up slope) to Stop 5a; cross altered rhyolite at about 700 feet.

32.1 Stop 5 - Section 30 Alteration Zone

This area is very close to the Dead River Shear Zone, an Archean zone of high strain and deformation. Alteration intensity varies from outcrop to outcrop, as does the dominant type of alteration. Chlorite is ubiquitous throughout the alteration zone, whereas sericite and carbonate are locally abundant alteration products. Alteration along this zone is interpreted to be synchronous with the

deformation. The stop has been divided into three parts which will be described separately.

This locality was mapped most recently by Baxter and others (1987) and lithologies are designated as the Highly Altered Variety of the Pillowed Basalt Member of the Volcanics of Silver Mine Lakes, Gabbro of Clark Creek, and Rhyolite Intrusive of Fire Center Mine. Location: NW¼, section 30, T49N, R27W.

5a. The Cliff Outcrops

This set of outcrops contains altered gabbroic rocks and intrusives of altered rhyolite porphyry. The outcrop on the south side of the valley is mainly altered gabbro with a fault-bounded block of altered rhyolite, which strikes approximately N50°E and dips 75° to the east, along the eastern contact. The western contact of this rhyolite block has a similar strike and a dip of about 40° towards the east. The maximum east-west thickness of the rhyolite block is 50 feet. Mineralization is concentrated along the faulted contact between the altered gabbro and altered rhyolite. Pyrite is the dominant sulfide phase, with arsenopyrite and chalcopyrite occurring in much lesser amounts. The small outcrop on the north side of the valley is a slightly less altered example of the gabbro.

5b. The Hillside Outcrop (about 225 feet east of 5a)

These outcrops are located along the north side of the valley on a gently upward sloping hill, and are mainly highly altered basalt. Near the south end of the outcrop is a rhyolite porphyry contact trending about N10°W and dipping 50° east. This is a good location to observe quartz-carbonate veining along the contact between rhyolite and altered basalt.

Between this outcrop and Stop 5c there are several smaller outcrops on the north and south side of the valley of predominantly altered basalts with rare rhyolite dikes.

5c. The Island Outcrop (about 225 feet east of 5b)

This outcrop is in the middle of the valley which is otherwise outcrop-free. The entire outcrop is highly altered basalt with the exception of the western 1/4 which is cut by rhyolite.

Proceed back to North Dead River Road and turn left (east) at 32.3 mi. At 34.3 mi, bridge over Clark Creek, park near bridge. Across the Clark Creek bridge, the road is known as Red Road.

34.3 Stop 6 (optional) - Pillowed Basalt and Rhyolite

The outcrops directly beneath the western side of the bridge are predominantly Archean pillowed basalt. These pillows are vertical and show younging direction toward S30°W. A fault contact (seen when the water level is low) juxtaposes a rhyolite porphyry on the east against the pillow basalt on the west. A few small (inch scale) zones normal to the main fault show shearing of the basalt into the rhyolite. This structural interleaving gives the rhyolite a pseudo-pillowed appearance. The large cliff, visible about 1500 feet to the north of the bridge, is the type locality for the Gabbro of Clark Creek.

This locality was mapped most recently by Baxter and others (1987) and contains the Pillowed Basalt Member of the Volcanics of Silver Mine Lakes and Rhyolite Intrusive of Fire Center Mine. Location: SE¼, section 29, T49N, R27W.

Continue north on Red road. At 35.0 mi, pull off to the right shoulder, near low relief outcrops.

35.0 Stop 7 (optional) - Granular rhyolite

These outcrops are along the upward slope on the east side of the road. Even though this rock is holocrystalline, it has been included with the other rhyolites based on its similar major and trace element chemical composition, e.g., calc-alkaline rhyolite on a Jensen diagram. The granular rhyolite consists of microcline and albite, but is now moderately altered to sericite, quartz, and minor epidote and chlorite. Some sulfide mineralization can be found in localized zones

of the outcrop, mainly on the south side.

This locality was mapped most recently by Baxter and others (1987) as Rhyolite Intrusive of Fire Center Mine. Location: NW¼. section 28, T49N, R27W.

Continue north on Red road. At 35.05 mi. cross Deer Creek and turn right (east) immediately after the bridge to a dirt road. At 35.35 mi, cross Deer Creek again. At 35.5 mi, 3-way intersection at the top of a hill, take road to the right. At 36.0 mi, flat area is part of the Clark Creek basin consisting of Lower Proterozoic Michigamme Formation; prominent outcrops on the left are Archean rocks. At 36.6 mi, pull over to small side road on the right and walk about 200 feet southwest to outcrops on small knob.

36.6 Stop 8 - Breccia

This outcrop is the best known exposure of a member which geomorphologically tends to form a depression. Stratigraphic top is towards the south-southwest, consistent with nearby pillowed basalt top indicators. This member consists of at least three lithologic breccia units. The lowest part of this member is interpreted to be a subaqueous pyroclastic and/or fine-grained mudflow deposit, devoid of large fragments. Above this is a breccia with a large proportion of fragments representing a wide range of lithologies. The majority of fragments are heterolithologic porphyritic volcanic rocks of probable andesite composition, now extensively altered. These fragments are equant to slightly elongate and sub-angular to sub-rounded. The other fragments are of iron-rich chert which occurs in shapes ranging from equant to highly elongate, with angular to sub-angular edges. This breccia is interpreted as a subaqueous mudflow, of relatively near-vent facies origin. An unbrecciated cherty iron-formation overlies this breccia, consequently the chert clasts must have been derived from pre-existing chert deposits that formed in a less stable environment.

This member has undergone a relatively large amount of strain, demonstrated by flattened clasts, compared to adjacent members. There are many replacement pods, consisting of mainly pyrite, throughout the member indicating hydrothermal alteration.

The large outcrops to the south of the breccia member are of relatively

unaltered gabbro. This gabbro shows a wide range of grain size, probably due to the localized fault movement which produced finer-grained zones within the overall coarse-grained rock.

This locality was mapped most recently by Baxter and others (1987) and contains the Breccia Member of Reany Lake of the Volcanics of Silver Mine Lakes and Gabbro of Clark Creek. Location: SW $\frac{1}{4}$, section 27, T49N, R27W.

Retrace route to Red road at first Deer Creek bridge and turn right (north) at 38.0 mi. Continue on the main gravel/dirt road and at 41.3 mi turn right (south) to gravel County Road 510. At 46.3 mi, turn left (east) to dirt road, the Holyoke Trail. Park near intersection and walk 1200 feet east on the road, then 160 feet southeast to Stop 9.

49.5 Stop 9 - Breccia

These outcrops, located along the extension of the Willow Creek Shear Zone, consist of a breccia member interbedded with pillowed basalt. The matrix-supported breccia consists of several types of flattened clasts (1:10 to 1:20) in a basaltic matrix. The margins of some clasts are feathered. The clasts vary in size from lensoidal 1/5 inch fragments to 4 inch wide and 6 feet long fragments. Clast types include rhyolite, gabbro, and granodiorite. The rhyolite clasts are porphyritic with 20% plagioclase phenocrysts in a fine-grained, quartz, plagioclase, and chlorite matrix. The granodioritic clasts are porphyritic with 40% plagioclase phenocrysts in fine-grained, quartz and chlorite groundmass. The gabbro clasts are medium-grained, sub-ophitic with plagioclase, chlorite and amphibole. The matrix of the breccia consists of mainly chlorite and epidote with up to 5% pyrite. This breccia is interpreted as a subaqueous mudflow which has undergone a high amount of strain.

This locality was mapped most recently by MacLellan and Bornhorst (1988) and is designated as the Breccia Member of Bismark Creek of the Volcanics of Silver Mine Lakes. Location: SE $\frac{1}{4}$, section 31, T49N, R26W.

Continue south on County Road 510. At 48.4 mi, pull off to right shoulder (outcrops on other side of road). Be careful, this road is heavily traveled at times.

51.4 **Stop 10 - Iron-Formation, Basalt, and Gabbro**

This outcrop consists of iron formation in contact to the north and south with massive basalt. To the west the basalt is cut by gabbro. The contact between the basalt and gabbro follows the highway. The iron-formation is approximately 5 feet thick and trends N30°W. It is composed almost exclusively of fine, black chert which contains scattered magnetite grains and abundant pyrite. To the west of this locality, the iron-formation member is generally layered with 1/2 inch chert and magnetite bands. Although the magnetite content can be highly variable, the iron-formation produces a strong magnetic signature. The basalt is dark green to black, fine-grained and relatively non-foliated. The gabbro is medium-grained, ophitic to sub-ophitic, and is composed of equigranular amphibole, plagioclase and chlorite.

This locality was mapped most recently by Puffett (1974) as the Lighthouse Point Member of the Mona Schist and Metadiabase of uncertain age. A more satisfactory correlation is with the Pillowed Basalt and Iron Formation Members of the Volcanics of Silver Mine Lakes and the Gabbro of Clark Creek as mapped one mile to the east by MacLellan and Bornhorst (1988). Location: SE¼, section 5, T48N, R26W.

Continue south on County Road 510. At 48.8 mi, intersection with North Basin Road and pavement begins, continue south. At 50.6 mi, pull off to right shoulder, just before going downhill and across a bridge. Walk east across road along an abandoned portion of 510 to small outcrops.

53.6 **Stop 11 (optional) - Archean greywacke**

This outcrop consists of black, quartz-feldspar-sericite-chlorite schist with minor disseminated pyrite; foliation trends westerly. This rock is interpreted as greywacke. This particular member extends eastward for 8 miles and represents the only major sedimentary unit within the Marquette Greenstone Belt. The member consists of greywacke and slate.

This locality was mapped most recently by Puffett (1974) as the Nealy Creek Member of the Mona Schist. Location: S $\frac{1}{2}$, section 10, T48N, R26W.

Continue south on County Road 510. At 50.85 mi, cross bridge over the Dead River Storage Basin. At 52.9 mi, bear left and at 53.0 mi, turn left (east) to the east end of County Road 502. At 53.6 mi, turn left (east) to U.S. 41 and return to the Ramada Inn in Marquette.

END OF DAY 1

Acknowledgements and References in Day 2 Road Log.

Geological Field Trip to the Marquette Greenstone Belt: Part II
Day 2 Road Log - Stops A to E

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NOTE: The field trip for Day 2 includes a late morning to afternoon stop at the Ropes Mine. There is a separate guide, Part III, authored by Brozdowski and Scott of Callahan Mining Corporation. Additional information on the geologic setting of the field trip stops may be found in the paper by Bornhorst (this volume).

Refer to Day 1 Road Log, Figure 1: **Route and Stop Map**

Mileage

0.0 Start Day 2 - Ramada Inn, Marquette

Assemble at the main entrance of the Ramada Inn. Turn right out of the parking lot of the Ramada Inn to Washington Street to U.S. 41 and then west towards Ishpeming. At 13.8 mi, turn right (north) at traffic light to County Road 573. At 14.6 mi, hairpin turn left. At 14.75 mi, pull off to the right shoulder alongside of outcrops.

14.75 **Stop A - Schist**

These rocks are foliated quartz-sericite schists with angular carbonate clots scattered throughout them. Foliation strikes N70°W and dips 84°S. The rocks are intermediate in composition (dacite) and have a calc-alkalic affinity. These rocks are interpreted to be subaqueously deposited volcanoclastic sediments or pyroclastic deposits, and are an important component of the southwestern part of the greenstone belt.

This locality was mapped most recently by Clark and others (1975) as the Kitchi Schist. Location: NW¼, section 34, T48N, R27W.

Continue NW on County Road 573. At 14.9 mi, Deer Lake is on right. At 15.55 mi, pull off to the right shoulder near glacially polished surface.

15.55 **Stop B - Breccia**

The breccia is exposed in a glacially polished outcrop and on the lake shore.

On the polished surface, the clasts vary from 10" X 14" down to the size of the matrix grains. Larger clasts, up to 2' X 4' in cross section, are present in the lake shore outcrops. Clasts greater than 1/2" make up about 20% of the rock and there is an obvious stratification in clast size. Shape of clasts varies from very-angular to rounded. The clasts are andesite-dacite (near compositional division) in composition with small chemical variation between individual clasts studied to date. This breccia is interpreted as a subaqueously deposited mudflow breccia.

This locality was mapped most recently by Clark and others (1975) as agglomerate facies of the Kitchi Schist. Location NE $\frac{1}{4}$, section 33, T48N, R27W.

Continue on County Road 573. At 17.5 mi, turn to left on gravel road to the Ropes Mine. See **Field Trip to Callahan Mining Corporation Ropes Mine Property** (this volume).

Retrace route back towards Marquette. At 34.2 mi, enter city of Marquette and at 34.5 mi, make a left turn on Washington Street towards the Ramada Inn. At 34.95 mi, turn left to Rublein Street and at 35.1 mi, turn right to Ridge Street. Pull over and park at 35.3 mi, near small outcrops on right shoulder.

35.3 Stop C (optional) - Schists

A small roadcut on the south side of Ridge Street exposes well-foliated chlorite-sericite schists. Foliation strikes roughly E-W and dips vertical. On the north side, about 200 feet through the trees, there is a clearing with glacially polished outcrops. On the way to the clearing there are layered amphibolitic schists (discussed further at Stop D). A banded, tabular body of quartz-sericite schist is well exposed at the clearing; this is interpreted as a rhyolite dike. The contorted banding is either due to primary flow banding and/or deformation. We consider the latter interpretation the most likely.

This locality was most recently mapped by Gair and Thaden (1968) as the Lighthouse Point Member of the Mona Schist. Location NE $\frac{1}{4}$, section 22, T48N, R25W.

Continue east on Ridge Street and at 35.4 mi, turn right to Lincoln Avenue. At 35.5 mi, turn left at traffic light to Washington Street. Continue straight on Washington Street past the Ramada Inn, from 36.1 mi until 36.6 mi, where Washington Street ends at Lake Street. Turn left on Lake Street. At 37.1 mi, make a right turn at the entrance to the Maritime museum and continue on road to the Coast Guard Station and park..

37.25 **Stop D - Lighthouse Point Member**

You must obtain permission from the U.S. Coast Guard to visit this locality.

No rock hammers allowed!!

Excellent shoreline exposures on Lighthouse Point provide a view of Archean and Proterozoic rocks. We will walk around the point noting the localities shown on Figure 2. This area was most recently mapped in detail by Gair and Thaden (1968) as the Lighthouse Point Member of the Mona Schist cut by Early Proterozoic and Keweenaw diabase dikes. Location: NW $\frac{1}{4}$, section 24, T48N, R25W.

Stop D1.

Archean, thinly layered, amphibolitic (basaltic) schist is cut by a tabular, porphyritic rhyolite dike trending roughly parallel to the layering. The layers on Lighthouse Point, as a whole, strike approximately E-W and dip 70°N. This layered schist was mapped by Gair and Thaden (1968) as the Lighthouse Point Member. The layers in the schist are interpreted as flattened pillows (basalt). The mechanism of flattening could be primary, but we interpret high strain as the most important means of flattening. The rhyolite is interpreted as an late-tectonic Archean dike. Some rhyolite dikes in the greenstone belt are more strained than others.

The Archean rocks are cut by two N-S trending diabase dikes that are metamorphosed to greenschist facies and are distinctly younger than the layered amphibolite-grade schist. Gair and Thaden (1968) interpreted these dikes as Early Proterozoic in age. However, Baxter and Bornhorst (1988) suggest these porphyritic dikes are Archean in age, correlative with the Matachewan dike swarm in Ontario.

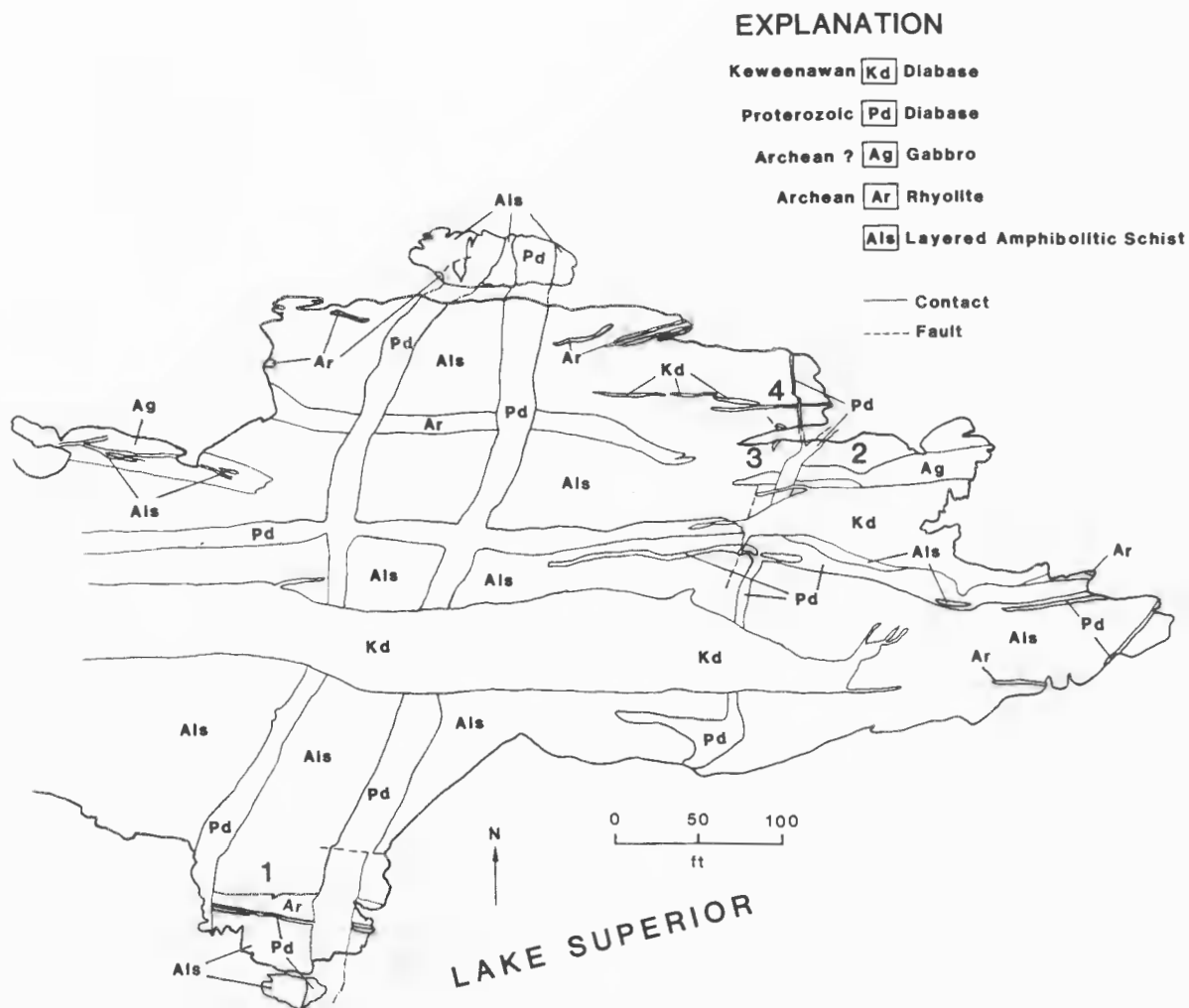


Figure 2: Geology of Lighthouse Point, Marquette, Michigan. Modified slightly from detailed map by Gair and Thaden (1968). Numbers at localities described in text.

Walk over ridge to other side of the point. A relatively unmetamorphosed, E-W trending Keweenawan diabase dike crops out along the crest of the ridge.

Stop D2.

There are bodies of comparatively massive, fine to medium-grained (Archean?) gabbro within the layered amphibolitic schist. This body must have been relatively late-tectonic due to the lack of foliation/strain as compared to the surrounding layered schists. Layered amphibolitic schist and gabbro are cut by a metamorphosed (Proterozoic?) diabase dike.

Stop D3.

Intense foliation has obliterated layering at this location; interpreted as a higher strain zone within the layered amphibolitic schist.

Stop D4.

Layered amphibolitic schist is cut by a metamorphosed (Proterozoic?) diabase dike. The metamorphosed dike and layered amphibolite schist are cut by a thin, relatively unmetamorphosed, E-W trending diabase dike of Keweenawan age. The metamorphosed diabase dike is offset by a small NW-SE trending fault.

Retrace route back to Lake Street. At 37.4 mi, turn right to Lakeshore Blvd. and proceed along the lakeshore towards Presque Isle Park. At 38.2 mi, junction with Fair Avenue, stay on Lakeshore Blvd. and at 38.7 mi, Lakeshore Blvd. joins Pine Street. At 38.8 mi, excellent view of active iron ore docks and Presque Isle (an Archean, serpentinized peridotite unconformably overlain by Jacobsville Sandstone). At 39.3 mi, turn left to Hawley Street before power generating plant. At 40 mi, turn right (north) to County Road 550. At 43.6 mi, pass turnoff to Sugarloaf Mountain overlook (requires climb along a maintained trail with steps). At 43.8 mi, large granitoid gneiss outcrops on both sides of the road. At 44.9 mi, turn right towards the lakeshore, opposite pathway to Harlow Lake, into a small parking area.

44.9 Stop E - Plutonic rocks at Wetmore Landing

Walk around the gate and down a dirt road to the lakeshore and proceed east. Walk SE along the road above the beach to large rounded wave-washed outcrops to view features characteristic of granitoid rocks which intrude the volcanic rocks

of the Marquette Greenstone Belt.

The dominant rocks are gneissic tonalite to granodiorite. These plutonic rocks are cut by tonalite dikes of varying age, by mafic dikes (amphibolite), and by veins of quartz of varying age. The mafic dikes are irregular in plan view and are deformed (Baxter and Bornhorst, 1988). Ductile to brittle shear zones cut the rocks; epidote is associated with the brittle shears. These outcrops display the complex history experienced by the granitoid rocks. These features are often obscured in more typical moss-covered outcrops.

This locality was most recently mapped in detail by Gair and Thaden (1968).
Location: SE $\frac{1}{4}$, section 29, T49N, R25W.

Return to Ramada Inn.

END OF DAY 2

ACKNOWLEDGEMENTS

This field trip would not be possible without support by the Michigan Geological Survey, Department of Natural Resources and the Department of Geology and Geological Engineering, Michigan Technological University for an on-going program of research on the Marquette Greenstone Belt. This field guide has benefited from reviews by J. Kalliokoski, Michigan Technological University, and K. Schulz, U. S. Geological Survey.

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**Geological Field Trip to the Marquette Greenstone Belt: Part III
Callahan Mining Corporation Ropes Mine Property**

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25 Industrial Park Rd., Negaunee, Michigan, 49866

NOTE: Additional information on the Ropes Mine may be found in the paper by Brozdowski in this volume.

STOP 1.

(Outcrop is 225 m west of the intersection of the Ropes mine access road with the paved highway: Park where access road curves to south and walk the final 40 m west along the cut line to a small prospect pit). Julius Ropes made his initial discovery of gold at or near this spot in 1880, and subsequently discovered the Ropes main ore zone 250 m to the west. The outcrop in the pit is a fine grained, massive to moderately foliated, quartz-sericite-chlorite rock with abundant 0.2 mm quartz grains and 1 - 2 mm rectangular mats comprised of aphanitic sericite in a matrix of aphanitic quartz, sericite, and chlorite. The sericite mats are interpreted as pseudomorphs after feldspar phenocrysts, because progressively more sericite altered feldspar phenocrysts are observable in this same rock type as the Ropes mine is approached from the west. No feldspar remains within or east of the mine. Toward the north side of the pit is well foliated quartz-sericite rock in contact with massive, rusty brown weathering carbonate-quartz rock with white carbonate veins.

STOP 2.

(105 m at azimuth 285 degrees from stop 1). According to a letter written by Julius Ropes in 1890, these two small quarries were excavated in the late 1880's to provide carbonate flux for a nearby iron ore blast furnace. The north wall of both quarries is a fine grained, well foliated, light-green carbonate-talc rock with lenses of blue-green talc and white carbonate veins. Massive, carbonate-quartz rock occurs toward the south ends of the eastern walls of both

quarries. Brown weathering, carbonatized, serpentized peridotite crops out uphill from the quarries.

STOP 3.

(Park across highway from Ropes mine access road, follow path southeastward to shore of Deer Lake). The serpentized peridotite at this locality has a well developed fine grained cumulate texture of 3-5 mm serpentine pseudomorphs after olivine and lesser pyroxene. The rock has curvilinear fracture fillings of chrysotile asbestos.

STOP 4.

Examine drill core and hand specimens of various types of ore and major types of wall rock from the Ropes mine property. View geologic maps of Ropes mine area and geologic plans and cross sections of Ropes mine.

Field Trip No. 2

Marquette Mineral District of Michigan

Mining History and Geology

by

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Cleveland-Cliffs, Inc.

and

Robert C. Reed
Michigan Geological Survey

May, 1988

MARQUETTE MINERAL DISTRICT OF MICHIGAN

MINING HISTORY AND GEOLOGY

Introduction

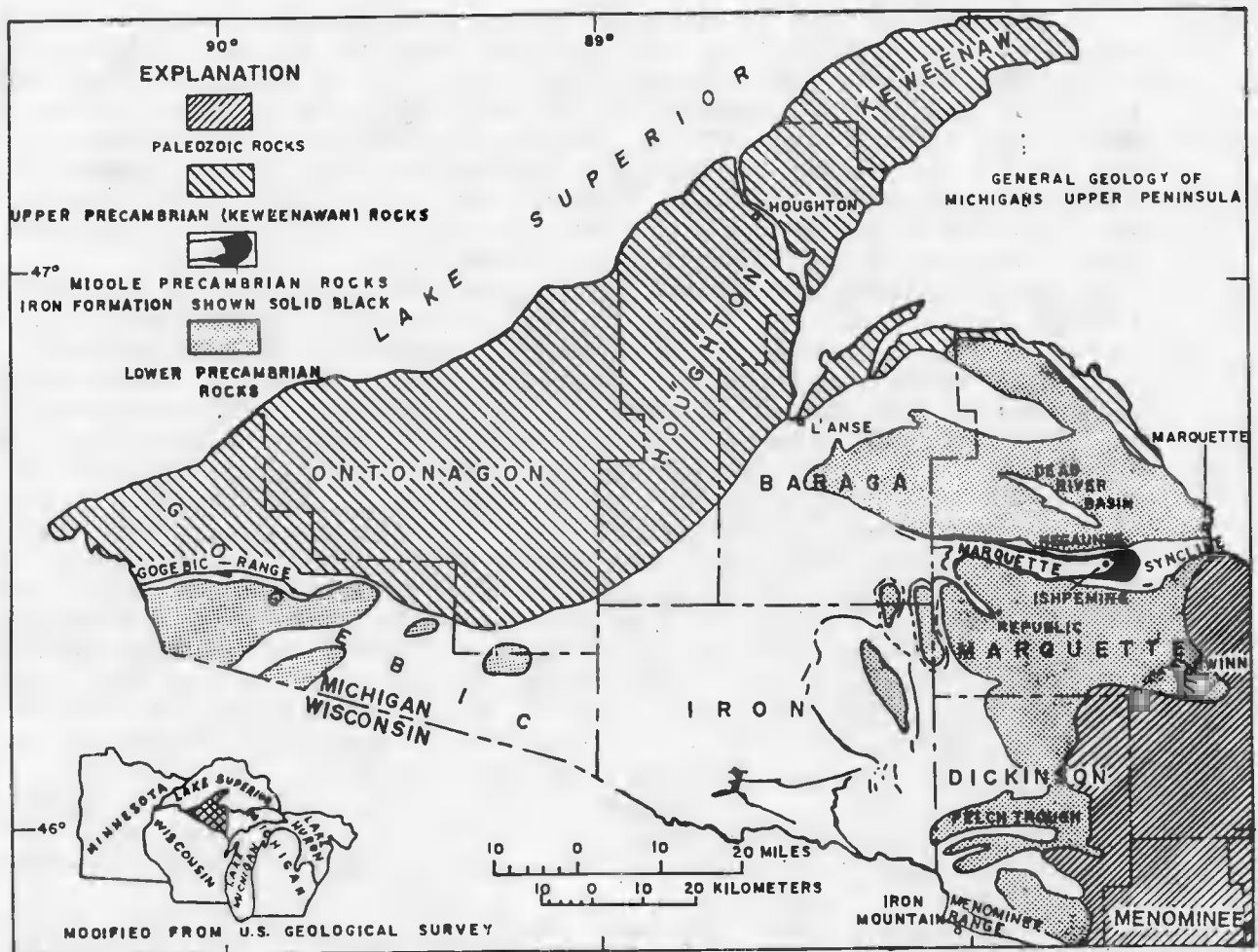
Welcome to the Marquette Mineral District situated in Marquette County and the eastcentral part of Baraga County in the Upper Peninsula of Michigan (Figure A)! This district was the first of the iron "ranges" of the Lake Superior region to be developed in the mid-1800's, and hosts the only iron mines still active in the Upper Peninsula, the Empire and Tilden Mines. The Marquette Mineral District also contains the only operating gold mine in the U.S. portion of the Lake Superior region, the Ropes Mine, and has known deposits of copper.

The dominant geologic feature of the district is the Marquette trough which contains rocks of the Marquette Range Supergroup, an Early Proterozoic sequence of mostly sedimentary and lesser volcanic rocks deposited unconformably on Archean greenstones and gneisses of the Superior Craton. The Marquette Range Supergroup consists of four groups (Cannon and Gair, 1970), from oldest to youngest, the Chocolay, Menominee, Baraga, and Paint River Groups. The three oldest are preserved in the Marquette trough, whereas the Paint River Group is found only in the Iron River-Crystal Falls District to the southwest. The rocks of the Supergroup record a progressive change in tectonic conditions from a stable craton (Chocolay Group) through a sedimentary basin with mild tectonism (Menominee Group) to a highly active tectonic basin (Baraga Group) as the long-stable Superior Craton was reactivated at the onset of the Penokean Orogeny. The time of deposition of the Supergroup is still poorly constrained, but deposition probably commenced about 2.1 b.y. and was terminated with the Penokean Orogeny about 1.85 b.y. (Morey, 1983). Keweenaw dikes cut rocks of the Supergroup, and the Jacobsville sandstone, of probable Keweenaw age, and lower Paleozoic sedimentary rocks unconformably overlie units of the Supergroup locally.

Pleistocene sand, gravel, silt, till, and clay were deposited over the district about 10,000 years ago during retreat of the last glaciers. Outwash deposits of silt, sand, and gravel preserved Quaternary trees, mostly spruce, in the Tilden Mine Gribben Basin Buried Forest near Palmer. The remains of more than 100 trees are preserved with their roots in place. Carbon 14 dates on material from these trees, which have as many as 150 growth rings, range from 9545 to 10,230 y.B.P. This indicates the recession of the Valdres (Great Lakean) glacier (Hughes, 1979). Figure B shows a cross section of the Gribben Basin forest.

Economic Considerations

The principal mineralization of the Marquette Mineral District has been iron, with some mangiferous iron ore. Total shipments of iron ore through December, 1987 were 590,776,442 long tons. The two active iron mines of the district, the Empire and the Tilden, each mine taconite type ore in open pit operations, and through the use of concentrators and pellet plants, produce a high grade product. Shipping ports for the taconite pellets are Marquette and Escanaba.

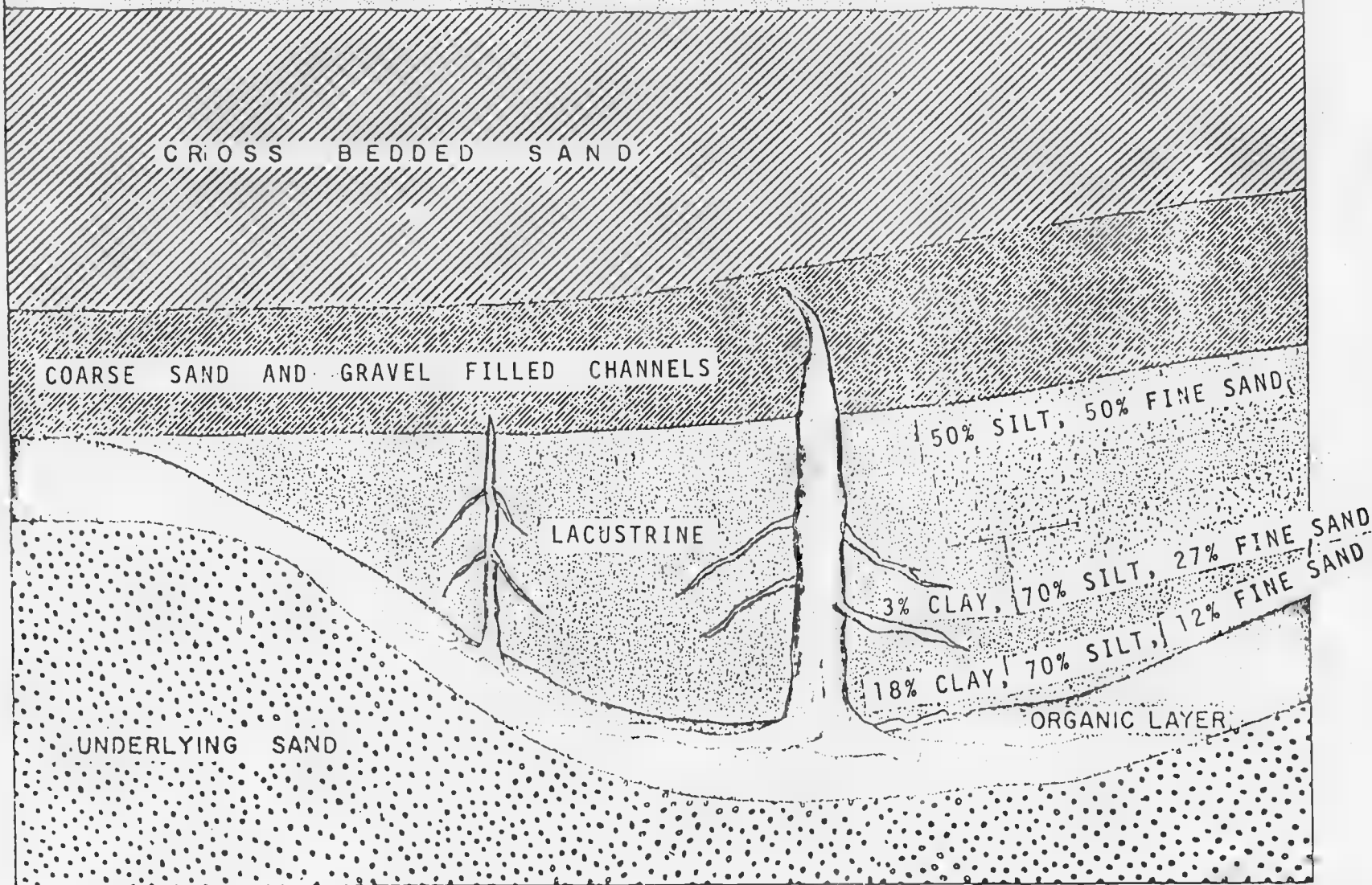


General Geology of Michigan's Upper Peninsula.

Figure A

Figure B showing cross section of Gribben Basin Buried Forest, Palmer

The Recession of the Valdres Glacial Ice, during time of Marquette-Munising Moraine
Circa 9,925 years B. P.



Prepared by John D. Hughes, Northern Michigan University, 1979

Figure B

The greater part of the district's iron ore has come from the Negaunee Iron-Formation of the Menominee Group. The Negaunee, one of the thickest iron-formations of the world, has a maximum stratigraphic thickness of over 1,300 meters (3,500 feet) in Negaunee and Ishpeming. Some iron ore was produced also from iron-formation, of unknown stratigraphic correlation to the Negaunee Iron-Formation, in the smaller Gwinn District to the south, and from the Bijiki Iron-Formation of the Baraga Group.

Today, taconite is the only ore type being mined. (The term taconite originated in Minnesota, on the Mesabi Range, after State Geologist N.H. Winchell proposed, in 1884, that the iron-formation was of "Taconic Age".) However, in the past, the major iron ores were direct shipping or natural ores of two main varieties. One was "soft" ore composed of soft, friable, earthy or semi-plastic hematite, martite and goethite. The other was "hard" ore composed of dense, compact specular hematite and magnetite. "Ore" is defined as a mineral or minerals from which a metal or metals can be mined at a profit.

The natural ores were found in three distinct structural settings. The soft ores were found in synclines and in fault structures at the base of the Negaunee Iron-Formation, and in fault structures on the intrusive sills in the upper portion of the Negaunee Iron-Formation. The hard ores were found generally at the top of the Negaunee Iron-Formation. Quantitatively, the total footwall soft ores shipped from the district was 186,607,540 long tons, the total sill soft ores shipped was 54,092,030 long tons, and the total hard ores was 60,350,944 long tons. Maximum thickness of the footwall soft ore was 80 meters (260 feet) normal to the bedding; maximum thickness of the hard ore was 30 meters (100 feet) (see cross sections, Figures C and D).

The Marquette Range is the only iron range in the Lake Superior Region to have extensive deposits of both hard and soft iron ores. The spatial distribution of these two ore types along the range appears to correlate with the grade of metamorphism of the host rocks. The soft ores are found mostly in the chlorite grade rocks in the Negaunee and Ishpeming area, and the hard ores mostly in higher grade rocks (ie. biotite, garnet, staurolite, to sillimanite grade) of the Republic metamorphic node (James, 1955; see Figure E).

Two principal hypotheses have been advanced for the formation of the direct shipping, natural ores; the "cold-water" hypothesis (VanHise and Bayley, 1897), and the hydrothermal hypothesis (Gruner, 1930). Today, most company geologists favor a hydrothermal origin for both the soft and hard iron ores.

Historical Summary

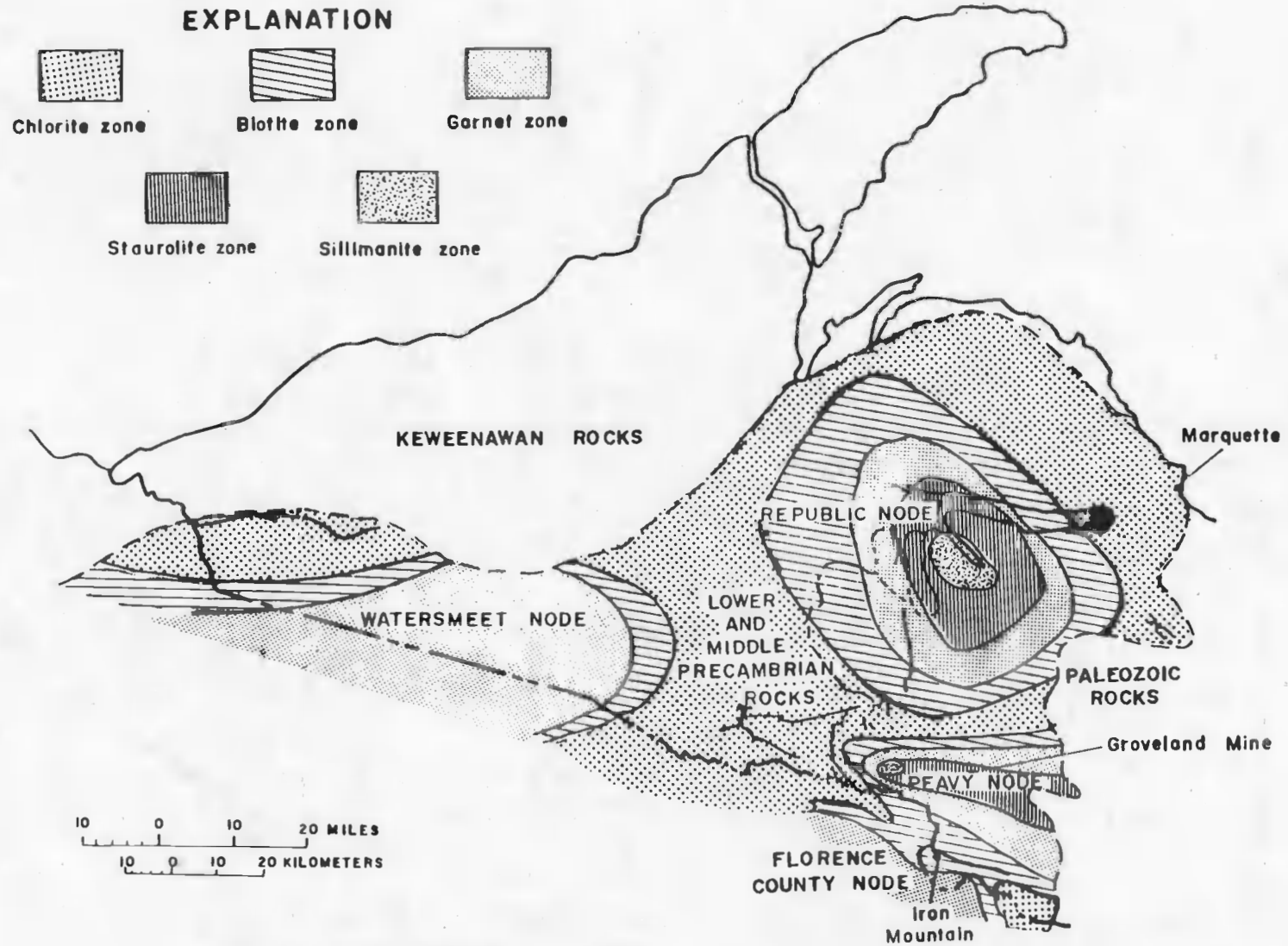
The extensive copper deposits of the Keweenaw Peninsula were worked by the ancients over 5,000 years ago and were known to the European explorers, missionaries and fur traders. The iron deposits were not known to the Europeans, although some were known to the native Americans who were very superstitious about them.

The Marquette Range was the first of the region's iron ranges to be discovered. The discovery was made by government surveyors subdividing the land into townships of 36 square miles. The survey party, under Deputy Land Surveyor, William Austin Burt, inventor of (See Figure E-1)

B-6



MAP SHOWING NODES AND ZONES OF PENOKEAN REGIONAL METAMORPHISM



Modified from James (1955) and Cannon (1973)

Figure E

Frank G. Matthews, Sr., Memorial Fund

★ HISTORICAL NOTES ★ NUMBER ONE ★

★ ★ ★ ★ ★ ★ ★

The Historical Notes are prepared to honor the memory of Frank G. Matthews, Sr., enthusiastic historian and collector of lore of early iron mining and charcoal iron making of Michigan's Upper Peninsula.

★ ★ ★ ★ ★ ★ ★



FRANK G. MATTHEWS, SR.

BURT'S SOLAR COMPASS

The Solar Compass of William Austin Burt revolutionized the early land surveying and land subdivision by providing a true north-south direction. Prior to this invention, the surveyor was completely dependent upon the magnetic compass, which could be unreliable due to the local magnetic character of the earth in the area being surveyed.

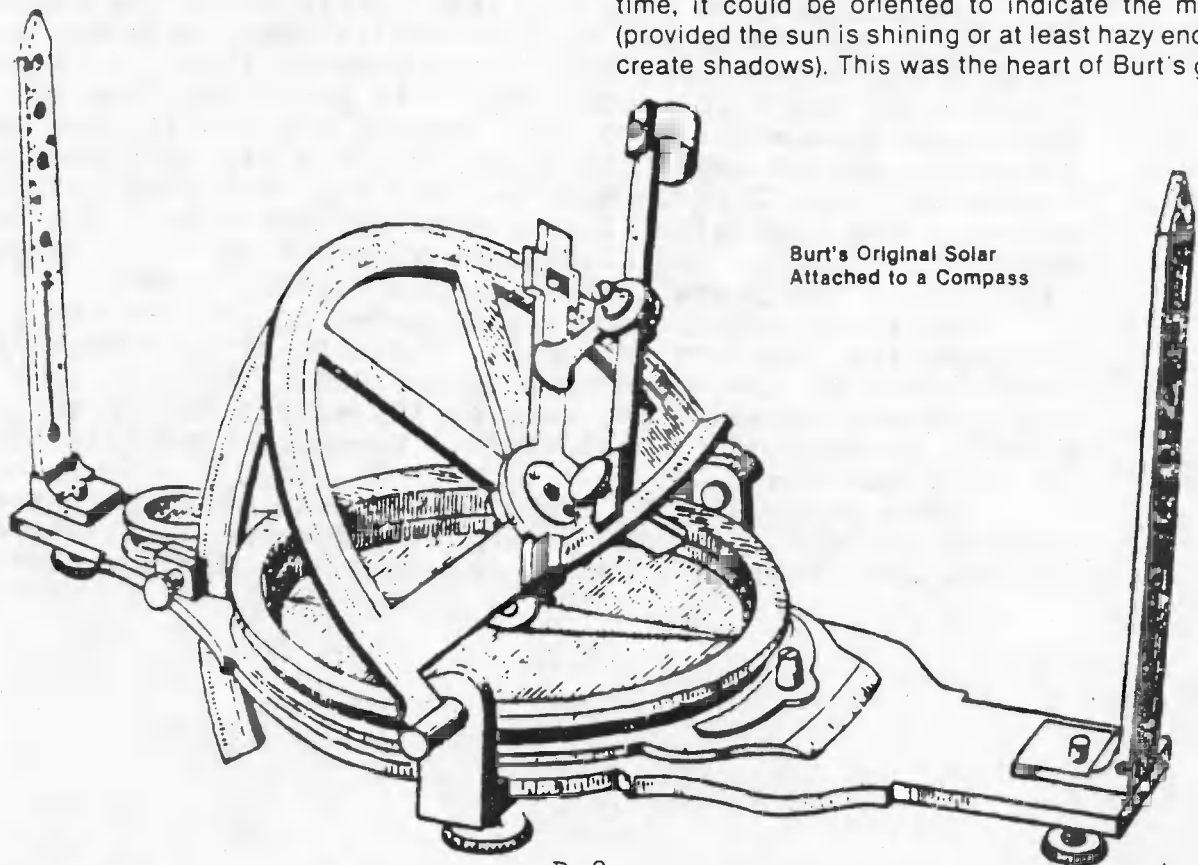
William Austin Burt of Mt. Vernon, Michigan, had been appointed a Deputy Land Surveyor for the Federal Government in 1833. In 1834 he surveyed an area north of Milwaukee in Wisconsin Territory. The area had local magnetic attraction causing great difficulty in surveying for Burt and other surveyors. In 1835 he worked on a model of his solar compass, then referred to as a "variation apparatus" or "variation compass." Variation referred to the amount of difference in degrees between true north and magnetic north. On February 26, 1836 he received patent

number 9428X for his invention. It was first used that year by him and by his son Alvin, also a surveyor. Here was his original device attached to the standard field compass of the day.

THE SUN DIAL

To understand how Burt's Solar Compass works, it is helpful to think of the sun dial, which most people have seen. The sun dial is an ancient device and has many forms. But the simple garden variety has a dial with the hours marked on it and an arm (called a "gnomon," from the Greek meaning one who knows or indicates) that casts a shadow read on the hour circle. If the sun dial has been correctly made and correctly oriented, the shadow will tell the time. At noon, the sun is in a true north-south line called the "meridian."

So, if one had a portable instrument and knew the time, it could be oriented to indicate the meridian (provided the sun is shining or at least hazy enough to create shadows). This was the heart of Burt's genius.



Burt's Original Solar
Attached to a Compass

the Solar Compass, on September 19, 1844, was running the township line between Range 26 West and 27 West south of Teal Lake in what is now the City of Negaunee. They noted that their magnetic compass pointed south in this area. Burt directed his party to look around and they found "spathose and magnetic ores abounding". However, news of this discovery was overshadowed by the rush for copper in the Keweenaw. In fact, the first iron mining company to operate in the region, the Jackson Mining Company, organized on July 23, 1845 in Jackson, Michigan, went to the Upper Peninsula looking for copper and other base metals, and was persuaded to look for iron by a half-breed, Louis Nolan. Although Nolan could not find the exposures of iron ore, the local chief "Marji Gesick" finally led them to the east shore of Teal Lake, in what is now Negaunee. This location was federal permit Number 158, and was secured by the Jackson Mining Company as Permit Number 593, Section 1, Township 47 North, Range 27 West, on October 4, 1845. Their intent was not to ship iron ore, but to ship iron "blooms" made from charcoal forges of the "Catalan" (Spanish) style like those used in New York and New England at that time, and used in Europe for over 2,000 years. They built a townsite on the Carp River, along with a dam and the Forge. The first iron blooms were made on February 10, 1848, and "mining" was by gathering high grade lumps of ore found on the surface at the Jackson Mine.

It was tough going for them and for the other charcoal iron operations that followed them. It soon became apparent to the managements of the mining companies, that the future of the iron industry lay in shipping iron ore rather than the charcoal iron blooms. However, the iron bloom industry limped along in the Upper Peninsula until 1898; over 1.8 million long tons of processed iron had been shipped from the Upper Peninsula.

The port of Marquette was founded in July, 1849. The first iron ore shipped, on July 7, 1852, consisted of six barrels. The opening of the Sault St. Marie locks in June, 1855 was a great boon to both the infant iron and infant copper mining ventures.

All of the first mines were open pit operations and were in hard iron ores. The hard ores cropped out on hilltops and also contained enough magnetite to deflect the magnetic compasses where concealed. The Jackson Mine led the way, followed by the Cleveland Mines at the east side of Ishpeming (Jasper Knob), the Humboldt, Republic, Champion and Michigamme Mines on the main Marquette trough, and the Isabella Mine on the Cascade Range.

The first underground mines opened in 1868 as the miners followed the iron ore in depth. The soft ores in Negaunee were found first at the Negaunee Mine in 1873. The soft iron ores did not crop out because they were easily eroded and were covered by varying amounts of glacial drift. However, some soft ores came up to ledge surface.

Crude geophysics by magnetic compass and the dip-needle helped in locating the iron ore bodies. The diamond drill was developed in 1876 and first employed on the Marquette Range in 1879.

Mining towns sprang up around the mines in what were termed "locations". Many towns were developed by the mining companies, with homes and "boarding-houses" subsidized by the companies to attract employees. There was a parallelism between the copper mining companies and their paternalistic efforts to obtain employees and retain them, and the iron mining companies. Foremost among the copper companies was Calumet and Hecla Consolidated Copper Company while the foremost iron company was the Cleveland Iron Mining Company (from 1891 it was The Cleveland-Cliffs Iron Company). C. & H. built the first hospital in Calumet before the company paid its first dividend. Cliffs also pioneered company houses, hospitals, and visiting nurses. They had the first pension plan in the Lake Superior Region, the first safety department, and employed the first company geologists.

Mining Methods

On the Marquette Range, by the 1880's almost all production came from underground mines. In the hard ore mines the principal method was open stoping (a stope is a Cornish word for a room) by the "room and pillar" method. Very little timber was employed for ground support. In the soft ore mines there was sublevel stoping, sublevel caving, square set mining, and top slicing. Much later, the concept of block caving was introduced and used extensively. Much timber was used for ground support in the soft ore mines and in the copper mines. One wag said "the best forests of Michigan are underground."

The choice of the mining method, and the use of wood or steel supports related directly to the geologic conditions. The hard ores were "competent" and would support an open span, while the soft ores did not have that strength. Other factors such as jointing, ground water, and depth from the surface all entered into both safety considerations and contamination of leaner material affecting the ore grade.

Metallurgical Beneficiation

For two generations, the Marquette Range iron ore that was mined and shipped, or used in the charcoal iron industry, was rich, natural, direct-shipping materials. Both the mining company officials and government geologists recognized that the iron-formations contained rich bands of iron minerals. The question was, how to separate these bands from the waste or gangue materials, essentially the chert or siliceous bands.

Beneficiation (to make "well" from the Latin) is the process or processes used to separate the valuable material from the gangue and generally consists of several steps. First is to crush and grind the feed material fine enough to "liberate" the valuable materials, making them essentially free of the gangue. The next step is to collect and separate the two materials into a "concentrate" of the valuable material from the worthless material, the latter called the "tails" or "tailings". The "feed" or crude material is called the "heads".

This beneficiation process (or processes) is termed "concentration". There are three principal means of concentration: gravity, magnetic, and chemical/physical. The gravity process utilizes the differences in specific gravity of the ore minerals in contrast to the gangue. This might be done with jigs, tables, heavy media, or siphonsizers, to name a few. Magnetic separation applies principally to magnetite.

Chemical/physical separation utilizes principally flotation, but could include electrostatic separation. Flotation uses the surface response of various reagents to various minerals. It is possible, in some instances, to "float" the ore minerals, or to float the gangue minerals. It is also possible, in some instances, to use a differential float to separate various ore minerals from one another.

Negaunee Concentrating Works

The first commercial concentrating plant on the Marquette Range was the Negaunee Concentrating Works built on the lands of the Jackson Mine. It used the jaspilite from the North Jackson Mine, paying a royalty of 45 cents a ton. The company, organized in 1881, built a plant 183 feet long, 116 feet wide and 113 feet high (nine stories), on a rock ridge towards Teal Lake. It had a 600 horsepower boiler, a boiler house, and an engine house. It used a jaw crusher, "Cornish" rolls, and rotary jigs. In its first year of operation, 1882, the plant produced and shipped 1,177 tons of concentrates. Production increased to 10,394 tons in 1883. The plant did not operate in 1884 and 1885, and it closed in 1886, years ahead of its time.

Edison's Mill, Humboldt

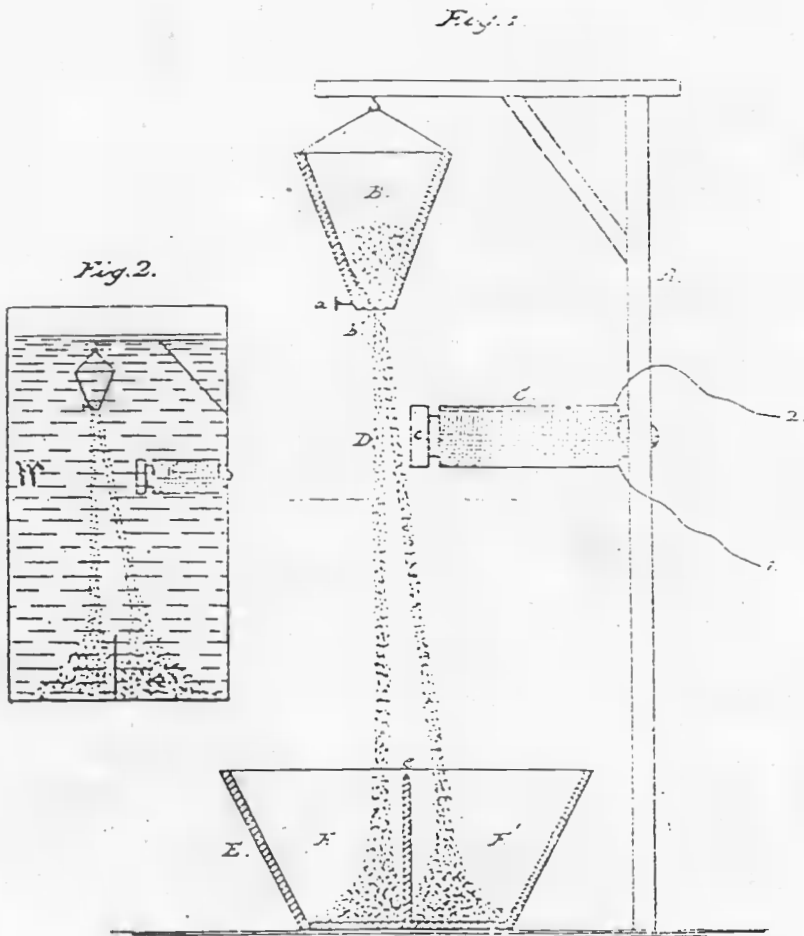
The second concentrating plant was built by Thomas A. Edison. He had patented his electromagnetic separator in 1880 (U.S. Patent Number 228,329 on June 1, 1880 (see Figure F)), after his research in 1879. Edison looked around the iron districts of the United States for an area with magnetic iron ores and heard of the Sampson Mine at Humboldt (also known as the Edwards or the Argyle Mines). He worked with Walter S. Mallory to construct the Concentrating Plant using magnetic ores and lean ores mined by the Sampson personnel. Edison's separator was different from the separators of

(No Model.)

T. A. EDISON.
Magnetic Ore-Separator.

No. 228,329.

Patented June 1, 1880.



Attest:

J. H. Howard

H. C. Keane

Inventor.

Thomas A. Edison

by Dyer & Wilber

Attys.

REPRODUCED FROM THE ORIGINAL DRAWING BY THE U.S. GOVERNMENT PRINTING OFFICE

the time in that it had no moving parts. It consisted of a feed hopper, a gate, the unipolar non-contact electromagnet, a partition, and bins for the magnetic concentrate and for the waste material.

The plant was built in 1888 and operated in 1889 as the Edison Iron Concentrating Company. It had a Gates jaw crusher, two 16 by 30 Cornish rolls, and screens sizing the feed to 20 mesh, a grain size for liberation. The iron concentrate analyzed 62 to 68 percent iron. The start-up had the usual problems such as breakdowns of the primary crusher and learning that 20 mesh was not fine enough for liberation. The intermediate product Edison called "mugwump". The plant burned in December, 1890 and was not rebuilt. He said "Well, its all gone, but we had a hell of a good time spending it" (his investment)!

The third mill to open was that of the Republic Reduction Company in 1888 and 1889; it was sold in 1891. The Michigamme Mine used a Swedish "Wenstrom" electromagnetic separator starting in 1889. Although early results were encouraging, the plant closed in 1892.

Minnesota Concentrating Efforts

After these early efforts at concentration in Michigan, the scene shifted to Minnesota. In 1902, the first concentrating plant was built at the west end of the Mesabi Range and used the Biwabik Iron-Formation for ore. Various plants followed, using gravity methods on the "wash-ores". Professor Edward W. Davis, of the Minnesota Mines Experiment Station, pursued a vigorous research program on the magnetic concentration of the magnetic portion of the Biwabik Iron-Formation, starting in 1914. The Reserve Mining Company was organized to mine the magnetic iron-formation and to use Davis' ideas for concentration. The plant operated in the 1920's, but closed due to two principal problems: (1) the difficulty of drilling blast holes, and (2) the high cost of concentration while competing with low cost, open pit mined natural ores.

The idea was revived in the 1940 by Professor Davis, who had continued to work on the problem. The Reserve Mining Company was reorganized and their first plant commenced operations after World War II on the "taconite" iron-formation. Shortly after, the fine grained concentrate was agglomerated or pelletized at Reserve Mining.

Michigan Low Grade Ores

During World War II, Cleveland Cliffs investigated various low grade iron-formations that could be amenable to commercial concentration. The research was directed into two areas: (1) the Bijiki Iron-Formation west of Michigamme, and (2) the hard ore jaspilite iron-formation at the old hard ore mines.

The Ohio Mine west of Michigamme tested well in terms of heavy media concentration. The opening of two open pits and the construction of a concentrator started in 1951. The first concentrates were produced in May, 1952. The plant operated until September, 1960 producing a total of 747,729 long tons of concentrate. This is not significant by today's standards, but it marked a dramatic shift from underground mining to the new era of open pit mining and concentration.

The jaspilite, or "jasper" as Cliffs called it, was being investigated at the Humboldt and Republic Mines. The mode of concentration was to float the specular hematite and magnetite in fatty acids. The Humboldt plant was built in 1952 as a joint venture of Ford Motor Co. and Cliffs, the same year the Ohio Mine opened. The first concentrates were produced in 1954, but no form of agglomeration was used.

Work had gone ahead at the Republic Mine and its first concentrates were produced in 1956, using the same flow sheet as the Humboldt Mine. The Republic Mine concentrates were shipped, starting also in 1956, to Eagle Mills, east of Negaunee, to a Straight Grate Plant to be pelletized. This plant had its share of problems, and Cliffs looked to a different process.

Cliffs worked with Allis-Chalmers Manufacturing Co. of Milwaukee to adapt the Grate-Kiln process, used in making cement, to produce iron concentrates. This was a first in the world-wide iron ore technology. This process was first applied at the Humboldt Mine with two identical "lines" in 1960. A second plant was started at the Republic Mine in 1962.

The Empire Mine, south of Negaunee and west of Palmer, was a magnetite rich iron-formation. Test work included the development of autogenous grinding (self grinding) mills and a combination magnetic separation and gravity methods. Later, flotation was added as the final step. The concentrates were pelletized by the ACL Grate-Kiln system. The first concentrates and pellets were produced in December, 1963.

The Pioneer Pellet Plant was started in 1964 to pelletize Mather Mine underground ores. This improvement in product, appealed to the steel plants and resulted in keeping this last underground mine operating until 1979.

The Tilden Mine had been an open pit operation producing a special grade of iron-formation called siliceous ore for use in the open-hearth furnace. Years had been spent on metallurgical research. But a "break through" occurred in April, 1967 from a joint research-development venture of Cliffs and the U.S. Bureau of Mines at Minneapolis. The mode of concentration developed was "selective flocculation flotation" to recover the non-magnetic hematite and goethite. The plant and pit were built in 1972-1974. The first pellets were produced in December, 1974.

The initial pit and plant at the Tilden Mine was sized at 4.0 million long tons of pellets per year, and was known as Tilden I. Provision had been made in the design for doubling the capacity to 8.0 million tons per year, or even to 12.0 million tons per year. The decision was made to build Tilden II and it commenced operations in 1979.

The Empire Mine had had a similar growth. Empire I started in 1963, Empire II in 1966, Empire III in 1974, and Empire IV in 1980. This brought the annual capacity of each plant to 8.0 million tons per year. The Republic Mine pit and plant have been on a "standby" basis since 1983.

Pellet shipments for 1987 were:

Empire Mine 7,417,703 long tons
Tilden Mine 4,458,620 long tons

In 1987 the Tilden Mine faced economic necessities and quality product review, and concluded that a new open pit source of magnetic ore needed to be developed to replace the present open pit mining of hematite and goethite material. A source of magnetic material was known on the Cliffs Drive, and necessary permits are being sought.

The Gogebic Range, the last iron range found in the Upper Peninsula, was the first closed, followed by the Menominee Range, leaving today only the Marquette Range active in the Upper Peninsula. Thus, the Marquette Range is still alive and continuing, 144 years after its discovery.

Institute of Lake Superior Geology

FIELD TRIP No. 2

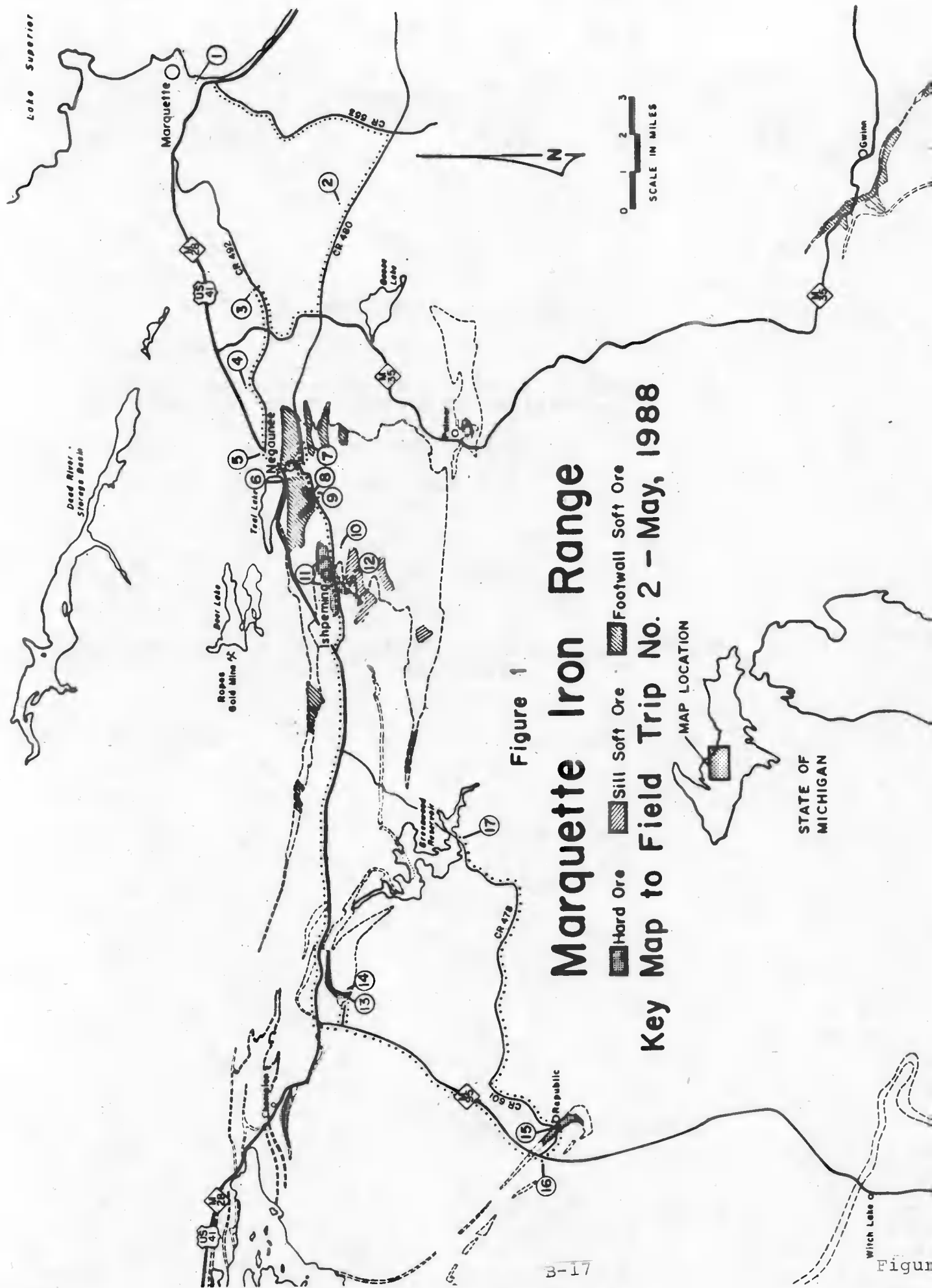
Marquette Mineral District of Michigan with
emphasis on MINING HISTORY and GEOLOGY

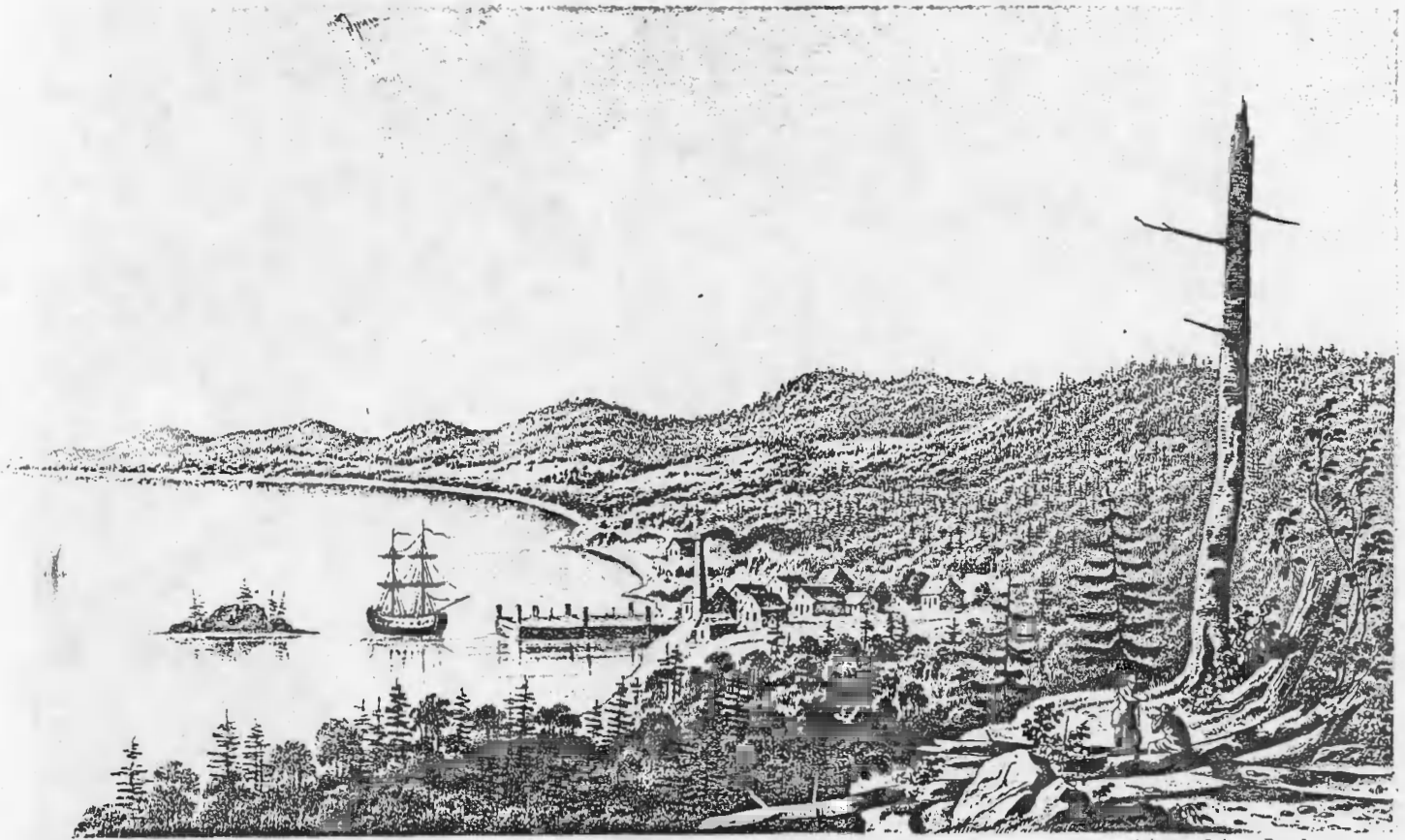
led by

Burton Boyum
Robert C. Reed
and
Wm. Kangas

May, 1988

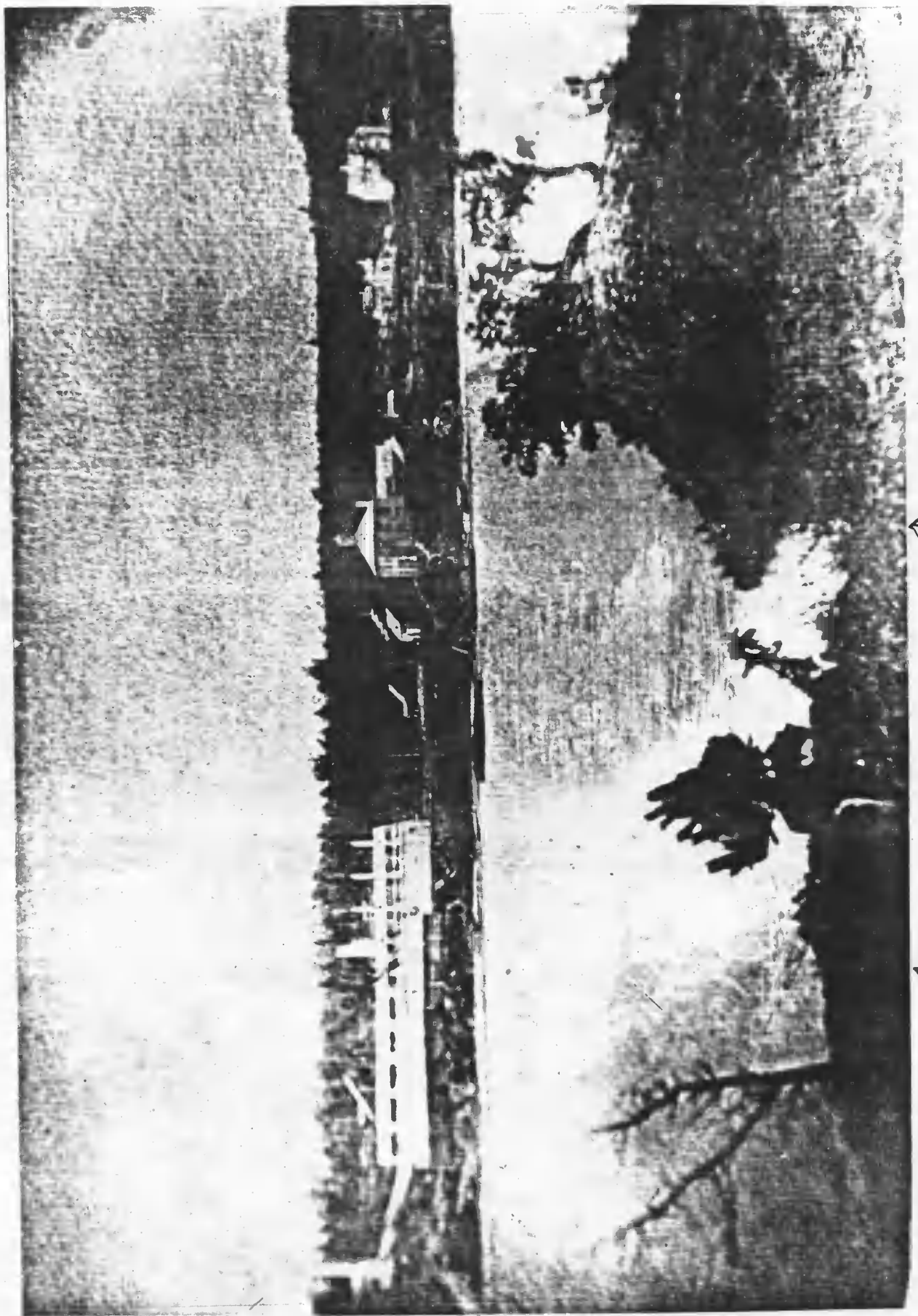
The KEY MAP, Figure 1, provided through the courtesy of
Cleveland-Cliffs, Inc.





Ackerman Lith. 379 Broadway N.Y.

VIEW NEAR CARP RIVER. LAKE SUPERIOR.



↑
Harlow House

↑
Sawmill - 1. 00

STOP 1 (Fig. 2 and 3)-- MARQUETTE HARBOR

The port city of Marquette was established July 10, 1849, as Worcester, the name of the home city of Mr. Waterman A. Fisher, a textile mill owner of Worcester, Massachusetts. Figure 2 shows a scene of the harbor in 1851, taken from Foster and Whitney (1851). Figure 3 shows the charcoal bloomery of the Marquette Iron Company and a part of the community in 1852, as seen from Ripley's Rock. This is the oldest known photograph of Marquette, as the name was changed in 1851.

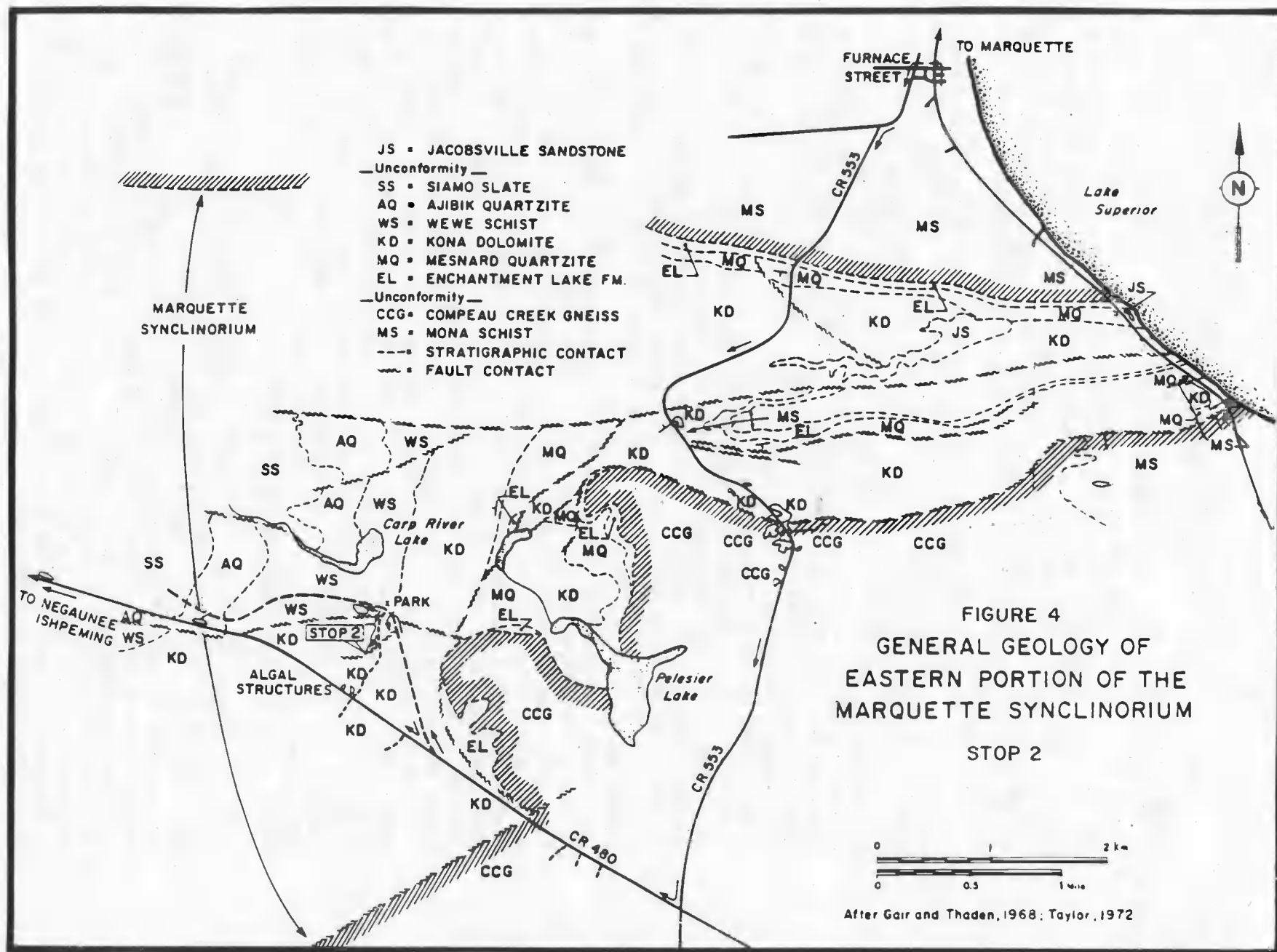
Mr. Fisher was the principal financier of the Marquette Iron Company, which was promoted by Mr. Robert Graveraet. Although the company had no mines, it built a charcoal iron bloomery on the shore of Lake Superior, using ore from the Jackson Mine. Previously, in 1847, the Jackson Mining Company had constructed a building in this area for both a habitation and a storehouse. The eastern backers of the Marquette Iron Company soon lost interest in the venture and they sold out to the Cleveland Iron Mining Company in 1853. The plant was destroyed by fire in 1853 and was not rebuilt because the Cleveland Iron Co. was putting its emphasis on shipping ore promoted by the start of construction of the Sault Ste. Marie (Soo) Locks. Agitation had gone on for years to build locks at the Soo, because all passengers and freight had to portage around the rapids each way. On August 26, 1852, U.S. President Millard Fillmore signed a bill authorizing the construction of locks and a canal.

The first water was let into the system on April 19, 1855, but there were leaks to be repaired. The first vessel to lock through was the steamer "Illinois", going "upbound", on June 18th. The brigantine "Columbia" carried the first cargo of iron ore, amounting to 132 tons, "downbound" in August, 1855. Thus, Marquette became the first iron ore port in the Great Lakes. A total of 1447 tons of iron ore was shipped from Marquette Harbor in that first year, all by the Cleveland Iron Mining Company.

The Cleveland Iron Company built its first ore dock in 1855. The Lake Superior Iron Company, Samuel P. Ely, Agent, built their ore dock next to them in 1857, but used a radically different design. The Lake Superior Iron Co. dock was 25 feet above the water and had "pockets" to hold the ore and chutes to drop the ore onto the deck or into the hold of vessels. This was the first ore dock with pockets built in the world!

STOPS 2 (Fig. 4)--KONA DOLOMITE and COPPER MINERALIZATION

This is the middle member of the Chocoy Group. It is essentially a fine to medium grained, pink to gray, crystalline siliceous dolomite with some interlaminated argillaceous and arenaceous phases. Hematite staining locally gives the rock a pinkish to reddish hue. Locally, there are large domal algal structures in the Kona. One classic locality alongside U.S. Highway 41, in Section 6, T47N, R24W, has been visited by countless geologists; however, we have chosen this series of exposures to show the algal structures.



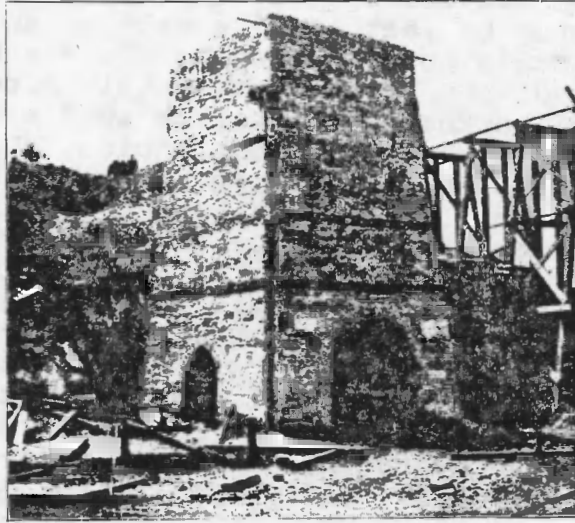
Copper Mineralization: A.R. Renfro wrote in Economic Geology, (1974): "Recently discovered sedimentary and geochemical processes of coastal Sabkhas provide the foundation for a hypothesis that successfully explains the genesis of these (copper) deposits". "Coastal sabkhas are evaporite flats that form along the subaerial landward margins of regressive seas. Because of their unique position, coastal sabkhas are nourished by subsurface flow of landward-migrating, low Eh-high pH sea water and by seaward-migrating, high Eh-low pH terrestrial water. Commonly they are bordered on the seaward side by intertidal mudflats and lagoons that are carpeted by leather-like mats of sediment-binding, blue-green algae. Fetid ooze consisting of interbedded decaying algae and detrital sediment occurs immediately beneath the living algal mat." "Coastal sabkhas and their related evaporite facies prograde seaward across adjacent algal-mat facies. Upon burial, the algal-mat facies becomes saturated with hydrogen sulfide generated by anaerobic bacteria. Concurrently, the trailing, landward edges of coastal sabkhas are buried by prograding terrigenous clastics of the desert. As sabkhas migrate basinward, terrestrial-formation water eventually must pass upward through the buried, strongly reducing algal-mat in order to reach the surface of evaporation." "Terrestrial-formation water initially has low pH and high Eh, and thus can mobilize and transport trace amounts of such elements as copper, silver, lead, and zinc. As terrestrial-formation water passes through the hydrogen sulfide-charged algal-mat, its load of solute metals is reduced and precipitated interstitially as sulfides."

The sulfides in the Kona dolomite are bornite, chalcopyrite, and pyrite. Estimates suggest a potential of 250 million tons of mineable material. This potential was not recognized until about 1896. Early prospectors in the area included Julian Case, J.M. Longyear, James Wilkinson, and Andrew Pings. Interest in the sulfide mineralization in the Kona died out by 1898, but was renewed in the 1970's, with drilling and mapping by several groups. Mineralization is not readily seen in place, but diamond drill core and hand specimens will be shown.

STOP 3 (Fig. 5)--MORGAN FURNACE

As noted in the Introduction, many of the early developers of the Marquette Iron Range had the concept of shipping the iron as blooms rather than as ore. As is typical, commercial development sprang up along the railroads, as they were developed. The Iron Mountain Railroad was incorporated February 22, 1855 and commenced operations in 1857. It was reincorporated February 6, 1857, as the Marquette and Ontonogan Railroad, and later as the Marquette, Houghton and Ontonogan Railroad (M.H. & O.), followed by the Duluth, South Shore and Atlantic Railroad (D.S.S. & A.); it is now known as the Soo Line Railroad.

A Mr. Schweitzer started a grist mill along the line some eight miles west of Marquette in a favorable location adjacent to the Little Carp River (later renamed Morgan Creek). Mr. Cornelius Donkersley, active in the railroad, felt this was a good site for a charcoal furnace. The Ely family of Rochester, New York, wealthy flour milling people, had taken an interest in the Marquette Range



Morgan Furnace. Built in 1863.

Figure 5

in the early 1850's. They encouraged Donkersley and financed the development. The good friend and legal counsel for the family was Lewis Henry Morgan. From the beginning, Morgan had advised them, and he also invested in the development. Starting in 1856, Donkersley had cleared the land and built houses for his workers. The Morgan Iron Company was incorporated July 1, 1863, and had an initial capitalization of \$50,000, made up of 2,000 shares at \$25 each. The Ely family joined Morgan in this venture. Annual production for the company was (in tons):

1863	337	1868	4023	1873	6324
1864	4023	1869-out of blast		1874	5973
1865	3489	1870	5952	1875	5377
1866	3749	1871	4755	1876	3278
1867	5057	1872	4356	1877	663

Total production of 57,573 tons

Lewis H. Morgan is noteworthy not only for his role with the railroads and with the furnace company, but also as a naturalist. He spent a number of summers on the Marquette Range observing the beaver. His treatise, "The American Beaver", was remarkable, and established him as an authority whose works are still respected.

STOP 4--MICHIGAN IRON INDUSTRY MUSEUM

This is the newest of the State of Michigan historical museums and is the outgrowth of a community effort dating back to 1973. A Michigan non-profit corporation, the Carp River Forge Bi-Centennial Park, organized an effort to honor the Carp River Forge. It raised money and purchased land for this purpose. In time, it joined forces with the Bureau of History, Michigan Department of State, and had the cooperation of The Cleveland-Cliffs Iron Company. The result became this Museum. Ground breaking was in July 1986 and dedication of the museum took place on May 16, 1987.

A. Tour of Museum and Rest Stop.

B. Convene in Frank G. Matthews, Sr. Memorial Museum

Remarks by Tom Friggens, Director, followed by a brief audial-visual program.

C. Solar compass demonstration (rain or shine).

The Historical Introduction has already commented on William Austin Burt and his solar compass. Attached is Historical Notes-Number One, which provides more detail. Also demonstrated is a sun dial compass, probably more used by field geologists than the Solar Compass.

STOP 5 (Fig. 6)--NEGAUNEE HIGHWAY CUT

This series of road cut exposures along U.S. Highway 41 contains, over a short distance, the Mesnard Quartzite, basal to the Chocolay Group; the Ajibik Quartzite, basal to the Menominee Group; and the Siamo Formation, the middle member of the Menominee Group. To the northwest, along the north side of the hill is a thin (one meter) basal conglomerate. The Kona Dolomite pinches out just to the east of these exposures.

The Mesnard Formation is a thick, vitreous quartzite, generally light gray, but sometimes with shades of pink. Numerous veins of quartz and hematite cut the bedding, and ripple marks and crossbedding are also present. This is the only member of the



Chocolay Group to be found this far west. Perhaps the other members were eroded here before deposition of the Menominee Group, or they were not deposited this far west from their principal area of deposition.

The Ajibik Formation is found in the next series of outcrops to the south. It is massive quartzite with minor amounts of argillaceous and conglomeratic material. In appearance, the Ajibik resembles the Mesnard Quartzite. Present in the quartzite is a distinctive concentric staining similar to Liesegang rings. Also present locally, are distinctive greenish granules.

The Siamo Formation consists of dark gray to light gray argillite, slate, graywacke and quartzite. Slaty cleavage is common to conspicuous. Locally, there are carbonate rich layers and beds of conglomerate. Also present are clastic dikes composed of material similar to the graywacke beds. The contact of the Siamo Formation with the Negaunee Iron Formation is not exposed here, but it lies just south of the Negaunee Branch Bank.

Also of interest is the Miners' Park with the pyramidal monument located on the west side of U.S. Highway 41. The monument was erected originally by the Jackson Iron Mining Company in 1905 before the company was sold to, and assimilated into, the Cleveland-Cliffs Iron Company. Because the monument was erected first in "Cornish Town", now an area of potential subsidence from the deep underground mining of the Mather Mine "B" Shaft, it was taken apart, each stone marked, moved, and reassembled on the present site by Cleveland-Cliffs, at its expense.

STOP 6--BURT SURVEY MARKER (NE CORNER, SECT.1, T47N, R27W)

This brief stop is adjacent to the Don Tresedder Insurance Agency, 109 U.S. 41 W. at the northeast corner of the section where William Austin Burt commenced his survey of the Town Line between Ranges 26 and 27. On the morning of September 19, 1844, he and his party went south and discovered the first iron ore of the Marquette Range. The marker was erected by the Marquette County Historical Society in 1987 as part of Michigan's Sesquicentennial.

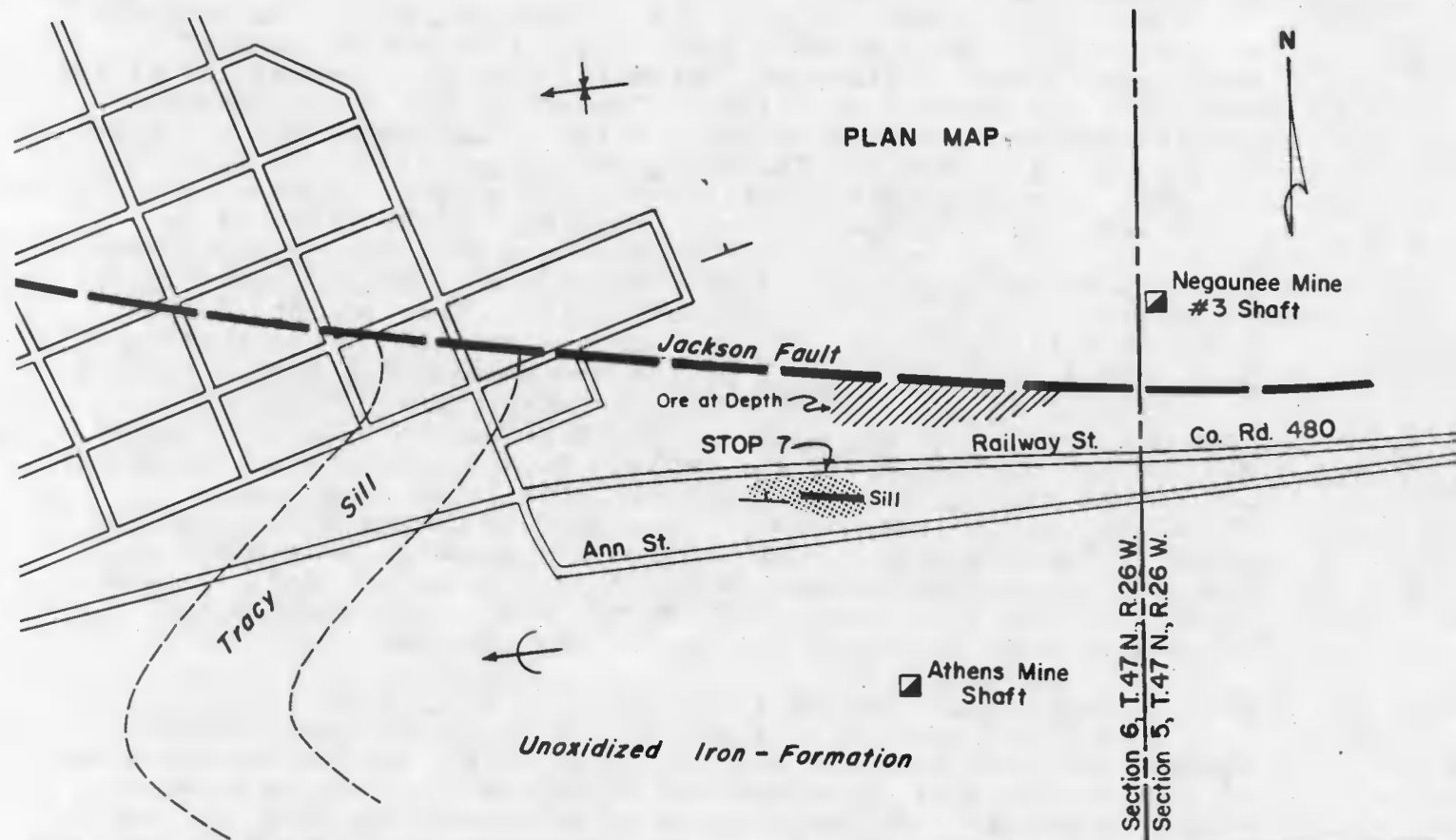
STOP 7 (Fig. 7)--RAILWAY STREET UNOXIDIZED IRON-FORMATION

This series of railroad cuts is ideal to examine the unoxidized, primary, cherty, iron carbonate iron-formation. Structurally, it is located in the faulted section that passed through the Negaunee Mine Number Three Shaft. It is on the north dipping limb of the Athens Enginehouse Anticline.

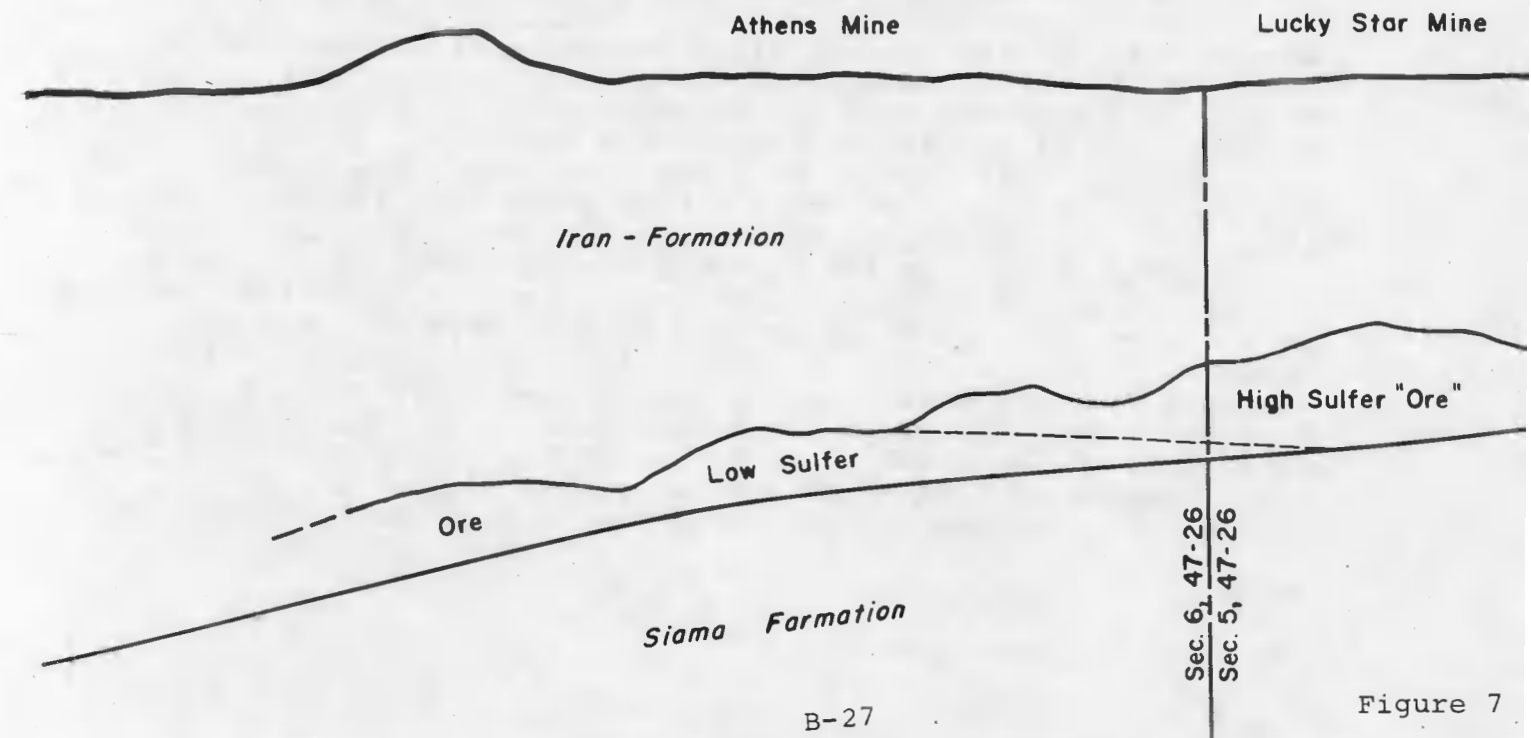
Although this section is unoxidized except for recent alteration, it lies just above a high grade iron deposit. Several thin sill-like intrusives can be seen in this exposure.

Worthy of note is the westward plunging zone of gypsum; the gypsum was formed after the iron ore. Figure 7 shows the structure of the zone in plan, together with an east-west longitudinal section, looking north. The ore-enrichment extended down the syncline from the Regent Group, through the Tracy Mine, the Lucky Star and Athens Mines, to the Bunker Hill Mine. The Lucky Star "Orebody" and the first three levels of the Athens Mine were never mined because of their high sulfur (gypsum) content. The enrichment under the railway street was also high in sulfur. This

FIGURE 7
PLAN MAP AND CROSS SECTION - STOP 7



LONGITUDINAL CROSS SECTION - LOOKING NORTH



condition existed also in the upper levels of the Mather Mine. The post-ore interstitial fillings of gypsum, calcite, and sometimes dickite and(or) halides have been found on the Gogebic Range, at the Zenith Mine in the Ely trough at Ely, Minnesota, and at the Steep Rock Mine at Atikokan, Ontario. The latter mine also had some arsenic minerals.

STOP 8--JACKSON GROVE: PASTY LUNCH AND REST STOP

The Pasty, as a meal, is a Cornish traditional miner's lunch. It was developed as a "package" that the miner could take underground and even reheat with a candle under his shovel! It continues to be a favorite around the world wherever the Cornishmen have gone.

STOP 8--SOUTH JACKSON MINE: MAGANESE MINERALS

The South Jackson Mine Pit is in a completely different geologic setting from that of the North Jackson Mine. The latter mine was in high grade hard ore. The South Jackson Mine was in intermediate (iron content) grade, soft ore. This ore, like that of the Lucy Mine to the east, was high in manganese, principally as manganite and pyrolusite. The ores from these mines were the only ones on the Marquette Range to be high in manganese. There were exotic manganese minerals found at the Champion Mine, such as manganiferous garnets, but The Champion Mine was in a different geologic setting, both structurally and in terms of metamorphic grade.

STOP 10--JASPER KNOB, ISHPEMING

This is a wonderful exposure of Jaspilite (the miners' hard ore jasper). Note the complex folding in the jaspilite and the irregular replacement by the hematite. To the south and west were lenses of high grade hard ore.

To the north are the hard ore open pits of the Incline, Sawmill, Schoolhouse and Little Mountain Mines. The first mining here was in 1848 by the Cleveland Iron Mining Company. The hard ore, which continued along the pitch of the synclinal axis that passes under the City of Ishpeming, was followed underground in the Cliffs Shaft Mine.

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 have been published in U.S. Geological Survey Monograph 28.

Folds having drag folds on their limbs and themselves being drag folds on the limbs of a still larger fold are strikingly shown 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 Early Precambrian Penokean orogeny and metamorphism. This theory would account for the 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. The rock here resembles megascopically, particularly in the very even bedding, magnetite-rich facies of iron-formation rather than hematitic facies, that is characteristically irregular bedded and oolitic.

STOP 11--CLIFFS SHAFT MINE, ISHPEMING

The distinctive obelisk style headframes of "A" and "B" Shafts were built in 1919, replacing the original wooden headframes erected when the shafts were sunk in 1873. The shaft sections show that both shafts cut "oar". Their ultimate depth was 1250 feet from surface. "C" shaft was sunk in 1954 to replace the two smaller shafts for more efficient hoisting of the ore. The Koepe hoisting system used in this shaft was the first such installation in the Western Hemisphere. It features an "endless rope" system with the hoist in the top of the headframe.

The Cliffs Shaft Mine, closed in December, 1967, had the longest production life of any mine in the Lake Superior region (1848-1967). It produced 28,960,406 long tons of high grade hard ore. Its greatest year of production was 1942 when 747,564 tons of ore were shipped. The "room and pillar" workings present under the town of Ishpeming, extend to 1250 feet below the collar of the shafts in the deepest (15th) level.

STOP 12--SOUTH PINE STREET, ISHPEMING

As noted in the Introduction, there are two structural locations for the soft iron ore. The ores in Negaunee and along the north rim in Ishpeming and the North Lake District are all on the footwall of the Negaunee Iron Formation. The second location is in fault structures on the big intrusive sills. The mines here were the Lake, Lake Angeline, Section 16, Holmes, and Salisbury Mines. Lake Angeline is a natural expression of the basin in which the Lake and Lake Angeline deposits were found. The lake was pumped out in 1890 to permit mining the soft ore on the lake bottom. These ores were very high grade, and had extensive botryoidal and mammillary hematite and goethite with numerous vugs. The Section 16 Mine, at the west end of Lake Angeline, had both

hard ore (above) and soft ore (below) in direct contact with one another.

These mines were the first on the Marquette Range to use electricity for electric for underground locomotives, lights, slushers, and pumps. It was here also that Cliffs voluntarily introduced the eight hour work shift in 1892.

STOP 13--HUMBOLDT MINE: EDISON HISTORICAL MARKER

This stop is at the historical marker erected by the Marquette County Historical Society in 1987 for the Sesquicentennial of Michigan.

This series of hard ore mines operated from 1865 to 1892 and from 1908 to 1917, producing 1,368,546 tons of hard ore from both open pit and underground operations. The Humboldt Mine was Michigan's first taconite type open pit, concentrator and pellet plant operation. It was in production from 1954 to 1970, shipping 9,433,305 long tons of concentrates and pellets.

STOP 12 (Fig. 8)--REPUBLIC MINE OPEN PIT

The Republic Mine was opened in 1870 as a series of hard ore open pits, but followed the near vertical dipping beds of the Negaunee Iron Formation into underground operations. The Pascoe shaft was an inclined shaft some 4,000 feet deep (2,910 feet vertically) with high grade, hard hematite and magnetite ore to that depth, in a host of jaspilite. From 1872 to 1926, the Republic Mine shipped 8,563,170 long tons of hard ore. It began as a taconite type operation in 1956, but closed in 1983 and is on "stand-by" basis.

The Republic pit is distinctive for its "high wall", the contact of the upper portion of the iron-formation with the metadiabase sill. The contact of the Negaunee Iron Formation and the overlying Goodrich Quartzite was marked by an extensive conglomerate made up of jaspilite. This conglomerate was higher in titanium than the underlying Negaunee Iron Formation.

As the open pit was developed, mining the iron-formation from the metadiabase footwall to the conglomerate and Goodrich Quartzite hangingwall, numerous underground workings were encountered. These openings were filled with broken crude ore so the drills, trucks, and shovels could work with safety.

STOP 15--HIGHWAY M-95 ROAD CUTS: MICHIGAMME FORMATION

Tightly folded schist of the lower slate member of the Michigamme Formation is exposed in a roadcut on the east side of highway M-95 near the axis of the Republic syncline. The rock here is iron-rich metasediment, now consisting of biotite-garnet-amphibole schist that contains a few inch-thick layers of impure quartzite. Although the rocks are in the sillimanite zone of metamorphism, sillimanite is not present here because of the lack of appropriate aluminous source materials. Minor folds, having amplitudes much greater than wavelengths and greatly attenuated limbs, are common and reflect the geometry of the major syncline whose preserved keel is deeper than it is wide at this point and becomes deeper to the northwest. Folding is markedly noncylindrical at outcrop scale; domains of homogeneous strain are commonly



only a few square feet. Most minor folds plunge northwest in accordance with the regional synclinal axis, but plunges vary from about 15° SE to 60° NW.

Near the north end of the outcrop, a thin (1 to 3 inches) quartzite bed is repeated many times by minor folds. Axes of adjacent folds only a few inches apart have plunges that diverge by as much as 60°. This noncylindrical geometry may be a result of an earlier fold set in the sedimentary rocks that formed prior to, and was strongly overprinted by, the folding which formed the Republic syncline.

STOP 16 (Fig. 9)--GREENWOOD RESERVOIR

The Greenwood Reservoir is a prominent new land feature created in 1973 by the Tilden Mining Company to provide a constant source of water for the concentrating plant requirements. The water surface approximates 1,400 acres. The Reservoir area is open to the public for fishing, boating, hiking, and other recreational activities. The agreement with the Michigan Department of Natural Resources provides that, at all times, the discharge downstream to the Middle Branch of the Escanaba River will be at least three times the minimum low flow observed by stream gauging over many years. An interesting feature of the system is the multiport discharge system in which any combination of four vertically arranged ports may be utilized to mix waters of varying temperatures and oxygen content.

The two principal granitic units forming the Archean Southern Complex will be seen here. Near point 8A (Fig.9) Compeau Creek Gneiss is exposed in a large roadcut. The Compeau Creek Gneiss is generally medium- to coarse-grained and mostly granodiorite or tonalite. It is characteristically both compositionally and structurally heterogeneous at outcrop scale. Here, it varies from massive rocks with faint banding or schleiren expressed by variations in percentage of mafic minerals, mostly biotite, to rather well foliated gneiss. Clots of biotite are common and in places are aligned in the foliation. Relict garnet cores can be found in some clots. Toward the northeast end of the road cut, the Compeau Creek Gneiss is cut by a nearly vertical dike of Early Proterozoic metadiabase.

This ends our trip. We hope that you have found this "sampler" of the Marquette Mineral District of interest.



FIGURE 9
A PORTION OF THE GREENWOOD
7 1/2 MINUTE QUADRANGLE
SHOWING THE LOCATION OF
STOP 17

Figure 9

FIELD TRIP 3

A STRUCTURAL TRAVERSE ACROSS A PART OF THE PENOKEAN OROGEN ILLUSTRATING EARLY PROTEROZOIC OVERTHRUSTING IN NORTHERN MICHIGAN: TEXT AND FIELD GUIDE

by

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INTRODUCTION

The Early Proterozoic Penokean orogen is one of several major orogenic belts in the North American craton that developed between about 1.95 and 1.85 Ga (Hoffman, 1988). Rocks of the orogen are exposed in Michigan, Wisconsin, and Minnesota (Fig. 1) and extend eastward into the Lake Huron area (Sims, et al. 1981), and westward in the subsurface into Iowa and Nebraska (Sims and Peterman, 1986). The southern boundary is not exposed inasmuch as it is overlapped by Phanerozoic platform sedimentary rocks. The Penokean orogen is intruded by 1.76 Ga anorogenic rhyolite granite which is exposed in Wisconsin.

The Penokean orogen consists of a northern assemblage of sedimentary and bimodal volcanic rocks of the Marquette Range Supergroup in Michigan (Cannon and Gair, 1970) and equivalents in Minnesota, the Animikie Group and Mills Lacs Group deposited on a continental Archean margin and a southern terrane composed mainly of Early Proterozoic calc-alkaline plutonic rocks termed the Wisconsin magmatic terrane (Sims, 1987 and in press). The magmatic arc terrane has not been recognized in Minnesota, although it may occur in the subsurface in southeastern Minnesota.

The Niagara fault zone is a broadly arcuate convex northward systems of faults and shears, as much as 10 km wide, that separates the continental margin assemblage and Wisconsin magmatic terrane (Fig. 2). It contains flattened, steeply dipping rocks that have prominent stretch lineations parallel to dip (Ueng and others, 1984; Sedlock and Larue, 1985; and Sims and others, 1985), and it is interpreted by the above authors to be the surface expression of a 1850 My old suture zone. In northeastern Wisconsin all of the components of an ophiolite assemblage, although dismembered, occur near the suture zone (Schulz, 1987a).

Following the initial suggestion of Van Schmus (1976), several authors (Cambray, 1978; Larue and Sloss, 1980; Greenburg and Brown, 1983; Anderson and Black, 1983; Schulz, 1983, 1984; Schulz and others, 1984; LaBerge and others, 1984; Sims and Peterman, 1984; Klasner and others, 1985; Sims and others, 1985; Klasner and Attoh, 1986; Schulz, 1987a, b; and Sims and others, 1987) have proposed a plate-tectonic scenario for the tectonic evolution of the Penokean foldbelt in northern Michigan and Wisconsin. Although they differ in detail, these authors suggest that evolution of the orogen began with rifting accompanied by formation of basins and troughs (such as the Marquette and Republic troughs) along the passive margin of the Archean Superior craton in northern Michigan. This was followed by subduction of oceanic crust to the south, with ultimate collision of arc-related volcanic and plutonic rocks with the Archean continental margin.

As a consequence of the accretion of arc-related crust to the Superior craton, widespread deformation of rocks of the continental margin as well as of the magmatic arc is to be

EXPLANATION

PHANEROZOIC (600 Ma and younger)



Sedimentary strata

MIDDLE PROTEROZOIC (900-1600 Ma)



Mafic igneous and sedimentary rocks of Midcontinent
rift system (1000-1200 Ma)



Anorogenic anorthosite and rapakivi granite (1480-1500 Ma)

EARLY PROTEROZOIC (1600-2500 Ma)



Granitoid rocks (1760-1800 Ma)



Volcanic and granitoid rocks of Wisconsin magmatic terrane
(1815-1890 Ma)



Stratified rocks of Animikie basin; Marquette Range Super-
group and Animikie and Mille Lacs Groups

ARCHEAN (2500 Ma and older)



Greenstone-granite terrane (2600-2750 Ma)



Gneiss terrane (2600-3550 Ma)



Extra-Superior gneiss and schist (2500-3000 Ma)

Great Lakes tectonic zone; dots, buried trace

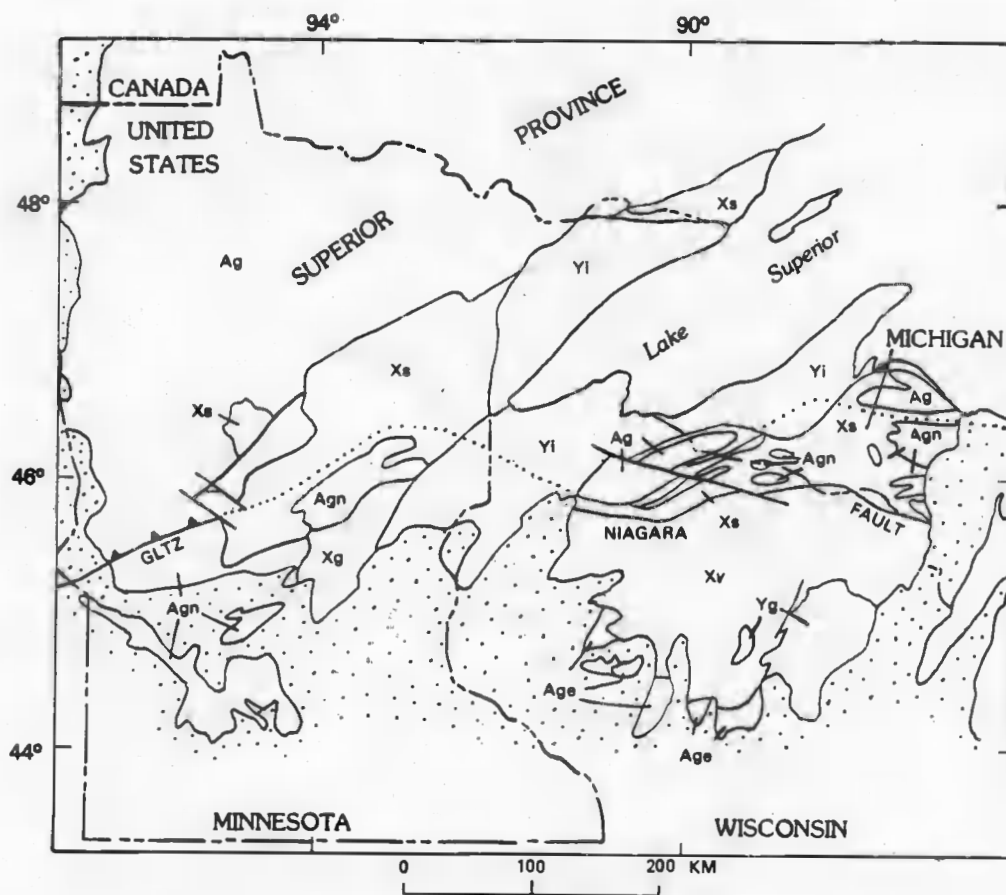


FIGURE 1. Generalized geologic map of the Lake Superior region showing rock units of the Penokean orogen and adjacent areas. Modified from Morey and others (1982).

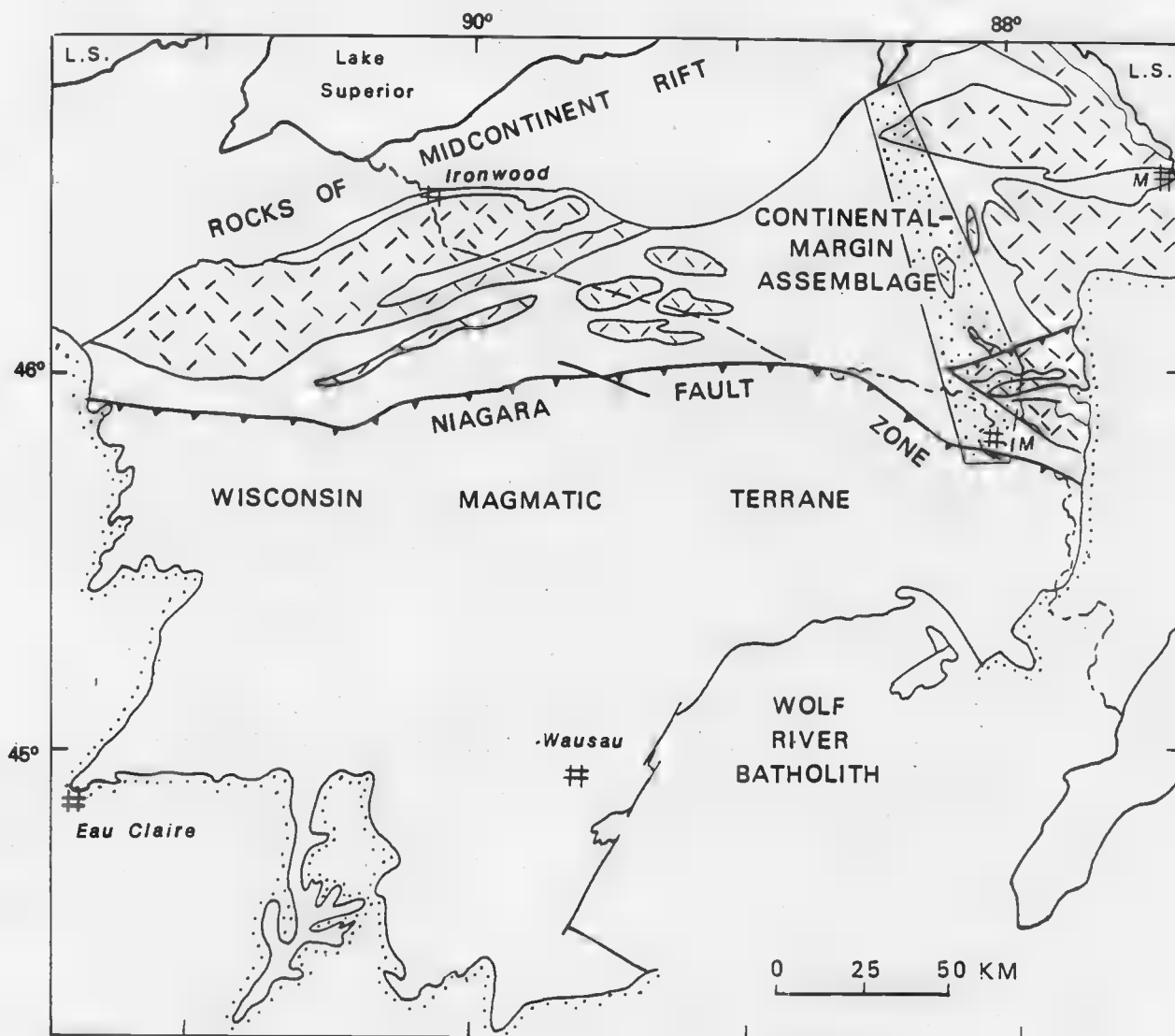


FIGURE 2. Map of the eastern part of the Lake Superior region showing extent of the Early Proterozoic continental-margin assemblage and Wisconsin magmatic terrane of the Penokean orogen. Archean rocks are patterned. Stippled area shows location of traverse in this field guide. IM = Iron Mountain; M = Marquette.

expected. In this guidebook, we examine evidence from northern Michigan showing that there was extensive overthrusting on the continental margin during the accretionary event. We examine the evidence for overthrusting along a north-south structural traverse (Fig. 2) extending from Falls River southward across the Michigamme basin, Amasa uplift, and Felch trough-Calumet trough region to the Niagara fault zone which lies along the Michigan/Wisconsin border.

This guidebook is mainly the outgrowth of field work and related synthesis done during 1986 and 1987. Critical areas for examination were selected from several excellent published geological maps and papers in the south (principally James and others, 1961; James and others, 1968; Bayley and others, 1966; Dutton, 1971). This was followed, where appropriate, by detailed structural studies in the north, mainly done by Klasner and Gallup. In this part of the area, previously mapped by mainly W. F. Cannon and Klasner (see for example Cannon and Klasner, 1972; Klasner, 1972; Cannon, 1973; Klasner, 1978), field work principally involved refinement and the addition of new detailed observations. Gregg's work has been in the Baraga basin, primarily northeast of the area covered in this report. Detailed studies at Falls River (Sikkala, 1987 and Sikkala and Gregg, 1987), however, mark the northern end of the traverse in the area of this report.

GENERAL GEOLOGY

Stratigraphic units of the Marquette Range Supergroup (Cannon and Gair, 1970) are listed in Table 1. The Marquette Range Supergroup consists of three groups which lie unconformably above, or in fault contact with, underlying Archean greenstone-granite or gneiss. The rocks occupy broad open basins, such as the Michigamme basin or relatively narrow, fault-bounded troughs such as the Marquette and Republic troughs (Fig. 3). An apparently thick sequence of metavolcanic rocks, the Hemlock Formation (see Cannon and Klasner, 1975 and Foose, 1980) lies along the west side of the Amasa uplift. As discussed below, we tentatively interpret this apparently large thickness of volcanic rocks as resulting, at least in part, from tectonic stacking during the Early Proterozoic overthrusting event. It should be noted that the Michigamme Formation is informally divided into an upper and lower slate member by the Bijiki Iron Formation Member (see Table 1). The lower slate member is the dominant lithology. Much of the evidence for overthrusting is found in the upper slate member (dominantly graywacke) member of the Michigamme Formation.

The Archean rocks of northern Michigan and Wisconsin have been divided by Sims (1980) into a granite-greenstone terrane (2600 - 2700 Ma) on the north and a gneiss terrane (2600 - 3550 Ma) on the south. The boundary between these two terranes has been named the Great Lakes tectonic zone. In the study area, it is oriented eastward and lies roughly along the Marquette trough (Fig. 3). The Penokeyan foldbelt is localized along the GLTZ,

TABLE I

		Michigamme Basin		Iron River syncline	Felch-Calumet trough
EARLY PROTEROZOIC	Marquette Range Supergroup	Paint River Group		Fortune Lakes Slate Stambaugh Formation Hiawatha Graywacke Riverton Iron-Formation Dunn Creek Slate	
		Baraga Group	Michigamme Formation Bijiki Iron-Formation Member Clarksburg Volcanics Member Greenwood Iron-Formation Member Goodrich Quartzite	Badwater Greenstone Michigamme Slate Amasa Formation Hemlock Formation	Bedwater Greenstone Michigamme Slate
			LOCAL UNCONFORMITY OR DISCONFORMITY		UNCONFORMITY
		Menominee Group	Negaunee Iron-Formation Siamo Slate** ** Ajibik Quartzite		Vulcan Iron-Formation Felch Formation
					UNCONFORMITY
		Chocolay Group	Not present	Saunders Formation	Randville Dolomite Sturgeon Quartzite Fern Creek Formation
			UNCONFORMITY	UNCONFORMITY	UNCONFORMITY
ARCHEAN			Granite - greenstone	Gneiss	Gneiss

* Upper slate member of the Michigamme Formation lies above the Bijiki Iron Formation Member and the lower slate member of the Michigamme lies below it.

** Possibly present in the subsurface of the Michigamme basin.

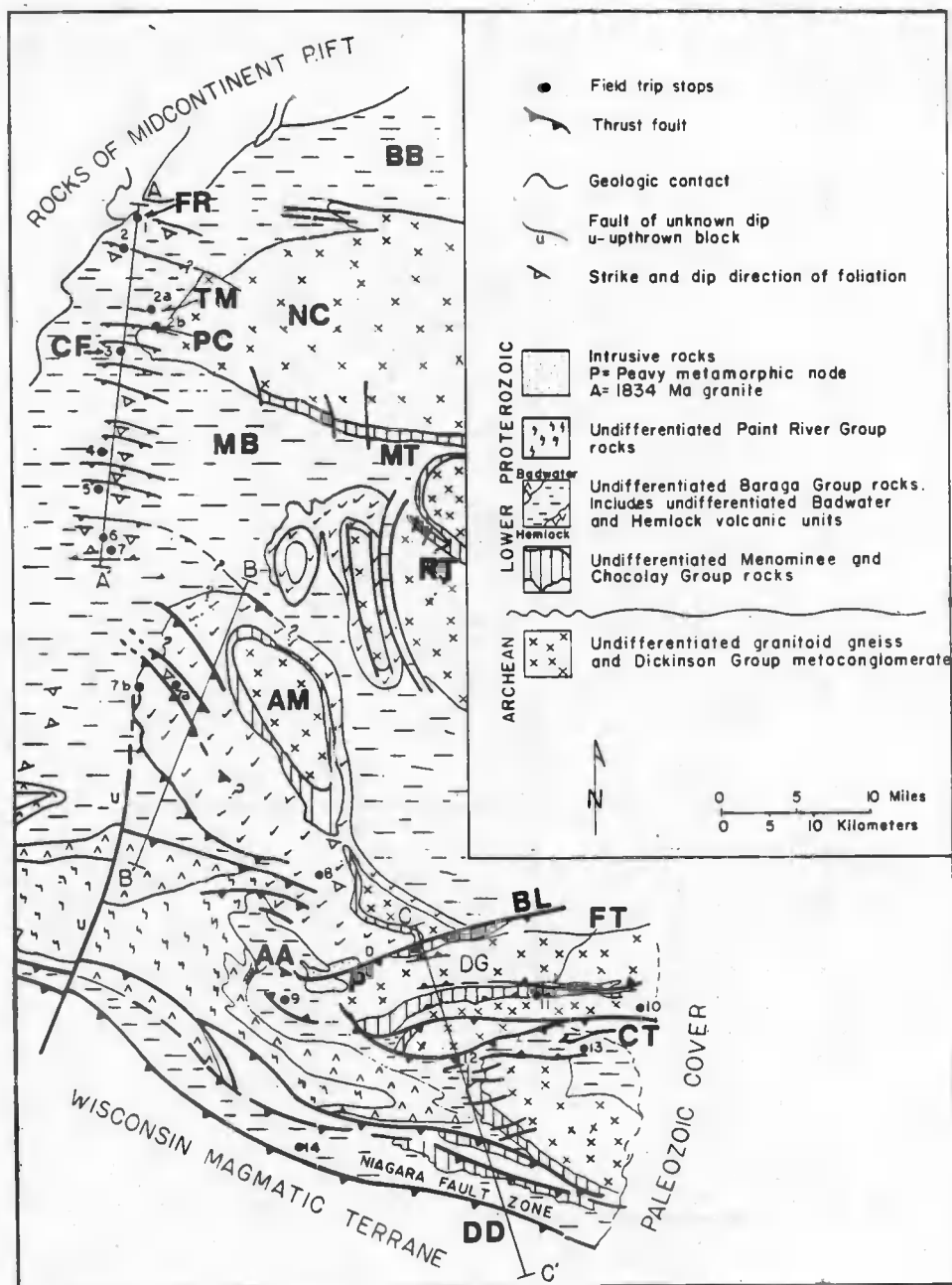


FIGURE 3. Geologic map of the study area showing major structural features, location of field stops, and location of structural profiles A-A' (Fig. 6) and B-B' (Fig. 8); C-C' is part of the composite profile (Fig. 9) which lies along a line connecting A to C'. Features discussed in the text include AM = Amasa uplift, BB = Baraga basin, BL = Bush Lake Fault, CF = Canyon Falls, CT = Calumet trough, DD = Dunbar dome, FR = Falls River location, FT = Felch trough, MB = Michigamme basin, MT = Marquette trough, NC = Northern complex, TM = Taylor Mine, P = Peavy metamorphic node, and PC = Plumbago Creek. RT = Republic trough. AA is the location of the granitic intrusion dated at 1824 Ma (Z.E. Peterman, personal communication). From Cannon (1983) and Dutton and Linebaugh (1967).

which appears to have played a role in the style of deformation of Early Proterozoic strata. North of the GLTZ, Early Proterozoic strata are only gently deformed, whereas south of it Early Proterozoic strata are intensely deformed. The traverse described in this guidebook lies mostly south of the GLTZ in the intensely deformed part of the Penokean foldbelt. Here, Early Proterozoic strata overlie block faulted Archean rocks (Cannon and Klasner, 1972 and Cannon, 1973).

At least four regional metamorphic aureoles (James, 1955) were formed during the Penokean orogenic event (Fig. 4). Attoh and Vander Muelen (1984) and Klasner and Attoh (1986) argue that the metamorphic aureoles were caused by crustal thickening, possibly due to tectonic stacking associated with overthrusting during the Penokean accretionary event.

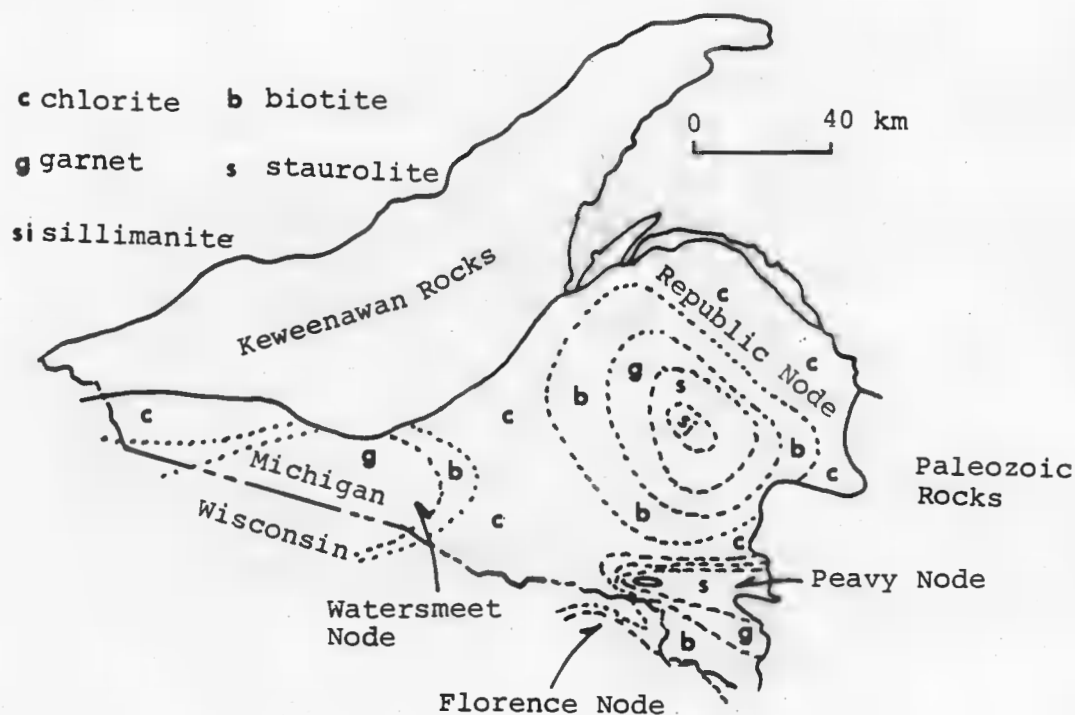


FIGURE 4. Location of metamorphic aureoles in northern Michigan (after James, 1955).

Structural studies (Cannon and Klasner, 1972; Klasner, 1972; Cannon, 1973; and Klasner, 1978) have shown that Early Proterozoic rocks in northern Michigan were subjected to at least three periods of deformation. The first event (F1) was thin skinned and resulted in shortening of Early Proterozoic strata and development of a widespread west-northwest-trending

structural fabric (Fig. 3). The second event (F2) involved block uplift of Archean basement rocks and formation of structural features such as the Marquette and Republic troughs and infolding of Early Proterozoic strata into the troughs. Larue and Sloss (1980) have shown that the troughs actually started to form early, during deposition of the sediments, and before F1 deformation. Klasner (1972, 1978) noted a third, late stage, brittle deformational event (F3) in the northern part of the Michigamme basin and suggested that it could have been caused by late block uplift of Archean basement. Petrofabric studies (Klasner, 1972, 1978) showed that regional metamorphism in this part of northern Michigan peaked after F1 deformation, about the time of F2 deformation.

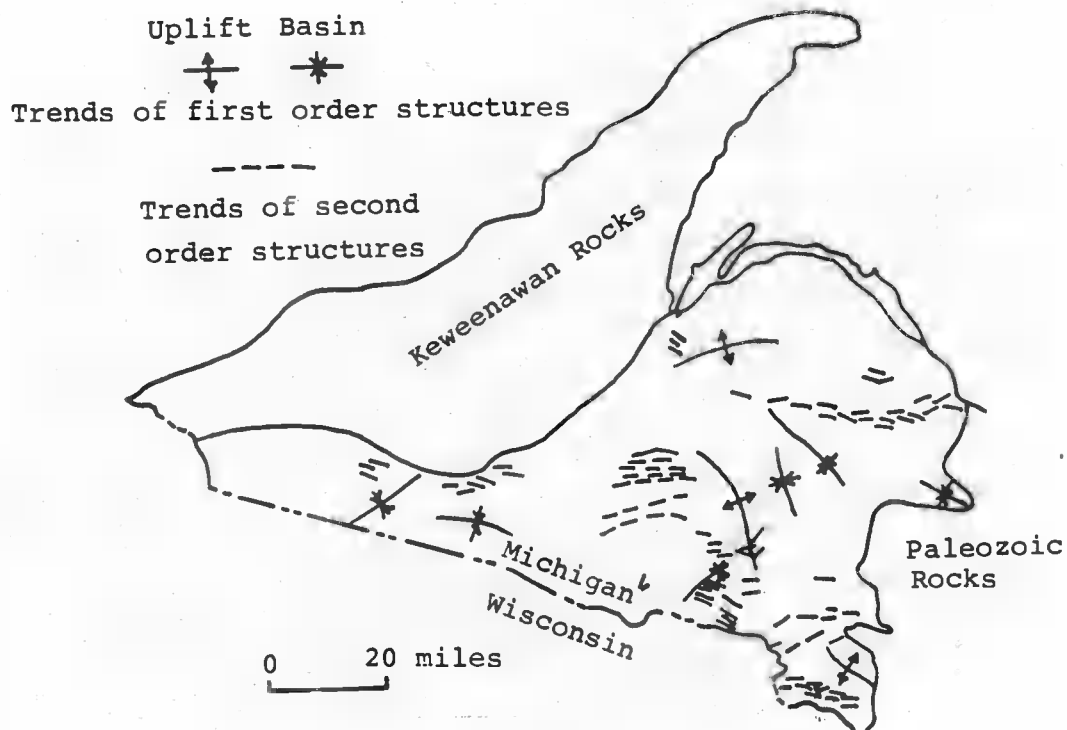


FIGURE 5. General trends of first and second order structures in northern Michigan (from Cannon, 1973).

Cannon (1973) divided the regional structures in northern Michigan into "first" and "second" order features (Fig. 5). First order structures have a wide range of orientations and are related to block uplift and doming (Sims and others, 1984a) of the Archean crust. Second order structures have a regular west-northwest trend and are related to the F1 shortening of Early

Proterozoic strata.

PREVIOUS EVIDENCE FOR THRUSTING OF EARLY PROTEROZOIC ROCKS

The dichotomy in style of deformation between Early Proterozoic rocks and underlying Archean rocks led Cannon and Klasner (1972), Klasner (1972), Cannon (1973), and Klasner (1978) to suggest that a decollement exists between them. They suggested that the shortening of Early Proterozoic strata relative to underlying Archean rocks was caused by gravity sliding off an ancestral Penokean mountain range in the south. They (in particular Klasner, 1972, 1978) suggested that F1 deformation occurred, in part, while the sediments were unconsolidated; however, this postulate is no longer tenable, and it appears that the F1 deformational event involved solid rocks.

Recently, Holst (1982, 1984) identified Early Proterozoic nappe structures in eastern Minnesota. Similarly, Maharidge (1986) proposed that the Felch trough area of northern Michigan (Fig. 2) represents a crystalline-core nappe feature. He based this interpretation on reexamination of sedimentary rock outcrops in the Felch trough area, previously mapped by James and others (1961), and on microstructural analysis of hand specimens from the region. Later, Sims and others (1987) tentatively suggested that the Felch trough area may represent the core of a north-verging nappe thrust structure, but this interpretation remains equivocal; and, as discussed below, although we cannot rule out the presence of a nappe, we think that Felch trough area may be part of a south-verging backthrust. Structural studies underway in this region should permit resolution of this problem in the near future.

On the other hand, Sikkala (1987) and Sikkala and Gregg (1987) have identified recumbent folds and a probable nappe structure in slate and graywacke of the Michigamme Formation at Falls River near L'anse. Similarly, Van Roosendaal (1985) mapped large scale west-northwest trending thrust systems in slates and graywackes of the Baraga basin (Fig. 3) northeast of Falls River.

Evidence for Early Proterozoic overthrusting has recently been found by Klasner and others (1988, in press) in several places in northern Michigan. About 120 km west of the traverse shown in Figures 2 and 3, Early Proterozoic slate and graywacke of the Tyler Formation (Baraga Group) near Ironwood, Michigan and metavolcanic rocks of the Emperor volcanic complex at nearby Wolf Mountain have a penetrative foliation that strikes roughly east-west and, when corrected for rotation due to deformation in the the ca 1.1 Ga Midcontinent Rift, dips gently south. This suggests that these rocks may have been involved in a thrust, or thrust-nappe event similar to that mapped about 100 km west in Minnesota by Holst (1984) and at Falls River by Sikkala 1987 and Sikkala and Gregg (1987). Klasner and others (in press) also

presented evidence to show that Archean crust is locally involved in the overthrust event. A drill hole about six kilometers east of Canyon Falls in the northern complex (Fig. 3) penetrated gneiss and underlying sheared slate and quartzite, all of which have low dipping foliation. The slate and quartzite are interpreted to be Early Proterozoic in age. Similar carbonaceous slate occurs at Taylor Mine and quartzite at nearby Canyon Falls. These relationships suggest that Archean gneiss was thrust over the Early Proterozoic slate.

Earlier studies in both Michigan and Wisconsin, nearer to the Niagara fault zone, support the idea of overthrusting on the continental margin. Bayley and others (1966), James and others (1961), and Bayley (1959) mapped local subhorizontal foliations in the Michigamme Formation, especially in the region between stops 9 and 13 (Fig. 3) just north of the Niagara Fault. Ueng and others (1984) attributed this foliation to vertical uplift of Archean basement. However, we attribute the subhorizontal foliation to thrust faulting, as discussed in some detail below.

Finally, thrusting resulting from the continent-arc collision has also affected rocks south of the Niagara fault. From geologic mapping and geochemical evidence, Sims and others (in press) have concluded that chemically dissimilar rocks in the Dunbar area (Sims and others, 1985) have been juxtaposed by thrust faulting and related deformation; and this interpretation accords with an earlier interpretation of Klasner and Osterfeld (1984) from gravity modelling that the Dunbar dome is allochthonous, either as a consequence of thrusting along the south-dipping Niagara fault or a subsidiary fault.

EVIDENCE FOR OVERTHRUSTING ALONG THE STRUCTURAL TRAVERSE

Geologic mapping and detailed structural observations at several selected field localities in the study area demonstrate the existence of small to moderate-scale thrust faults and locally related recumbent folds. These features are particularly well exposed at Little Mountain (field stop 2) near the northern end of the traverse, and subhorizontal foliation and related overturned to recumbent folds are present at several localities, especially, as mentioned above, at Falls River (field stop 1), and in the broad area encompassed by stops 9, 12, and 13 (see below). From these observations, larger-scale thrusts and possibly nappes can be inferred where permissive structural features are observed in the rocks and/or where previously mapped faults are better interpreted as thrusts.

To illustrate the style of Early Proterozoic deformation in northern Michigan, we have compiled the geologic map shown in Figure 3 and have constructed two interpretive cross sections (Figs. 6, and 8). The thrust system depicted on Figure 3 displays an overall northward sense of structural vergence.

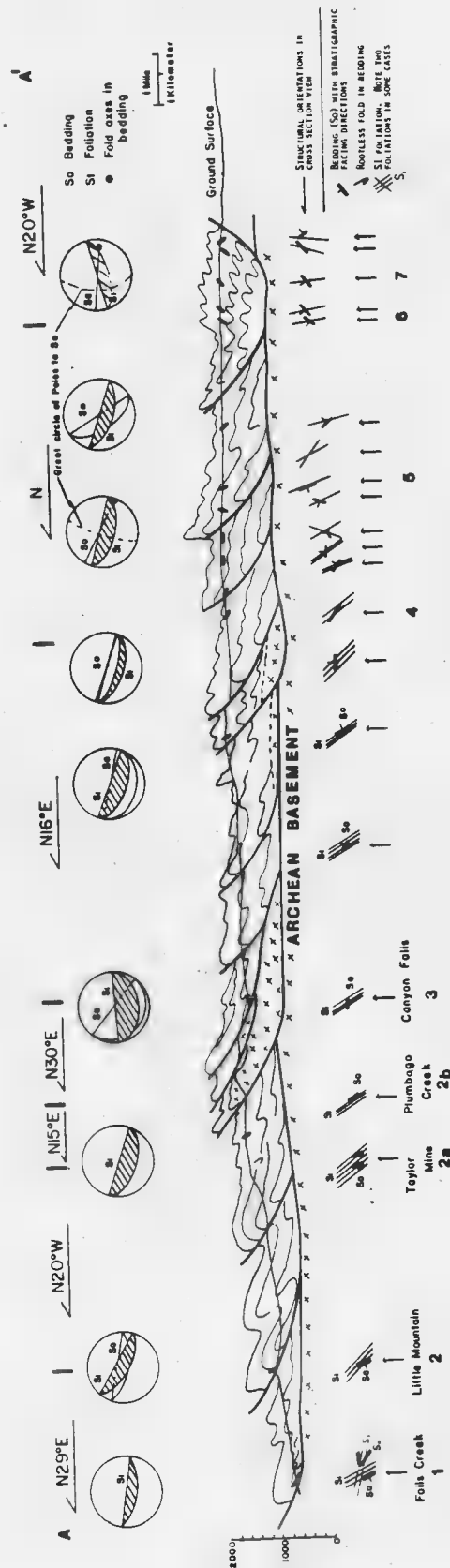


FIGURE 6. Structural profile A-A'. Note field stop localities. See Figure 3 for location. Lower hemisphere stereoplots illustrate orientation of bedding (S0), foliation (S1), and fold axes (black dots) along the traverse. Directions of each segment of the profile between stops are shown by arrows at top of figure.

The style of deformation in the Michigamme basin is illustrated on section A-A' (Fig. 6). Structural data in primarily the upper slate member of the Michigamme Formation along this profile suggests that the Early Proterozoic rocks were deformed as part of an imbricate thrust system. As shown on Figure 6, there does not seem to be much involvement of the Archean rocks in the thrusting. Structural relationships at Taylor Mine, Plumbago Creek, and Canyon Falls (Fig. 3), however, indicate that there was some involvement of the basement in the thrusting. At Canyon Falls flat-lying quartzite lies unconformably on Archean basement and has only minor evidence of Early Proterozoic deformation. Yet at Taylor Mine, about 5 km to the north, Early Proterozoic slates are overturned toward the north and have steep south dipping foliation as shown in Figure 7. At Plumbago Creek, 1.6 km south of Taylor Mine, penetratively deformed Early Proterozoic phyllite has a south-dipping foliation which projects beneath Archean gneiss. These structural data, when plotted on the elevation profile, as shown on Figure 6, indicate that there was some involvement of basement rocks in Early Proterozoic overthrusting in this region. Because of difficult access, outcrops at Plumbago Creek will not be visited. Taylor Mine is an alternate stop.

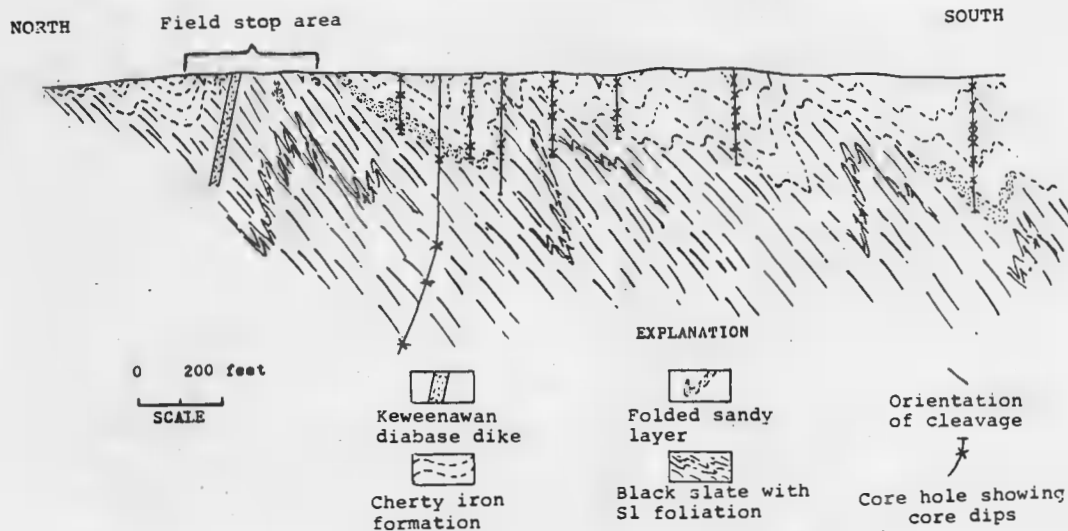


FIGURE 7. Structural cross section in the Taylor Mine area (location 2a on Fig. 3) showing S1 foliation and style of deformation. Diamond drill-hole data are from Ford Motor Company (After Klasner, 1972).

The main feature illustrated on section B-B' (Fig. 8) is that the large apparent thickness of Hemlock volcanic rocks (see Foose, 1980) along the west side of the Amasa uplift may, in part, be accounted for by tectonic stacking. Structural data at alternate field stops 7a and 7b lend support for the idea of tectonic thickening of the Hemlock. At stop 7a mafic volcanic rocks are intensely deformed and have a prominent foliation that is oriented northwestward, as shown on Figure 3. Stretch lineations on the foliation surfaces plunge steeply toward the west. At station 7b axes of small drag folds in siliceous slate plunge gently northwestward and their Z-shape symmetry indicates a northeastward sense of vergence. Thinly layered tuff at alternate stop 8 has a penetrative foliation that is oriented N55°W, 60°SW, and other outcrops in the region have similarly oriented foliations. Taken together, these and other outcrops on the west side of the Amasa uplift indicate that tectonic stacking could have significantly thickened the Hemlock volcanic pile. The nature of the stacking, however, is not resolved at this time. Profile B-B' (Fig. 8) suggests that it is an imbricate thrust fan. Alternately, the Amasa uplift may represent a domed duplex system. Either style of deformation would account for the thick section of Hemlock volcanic rocks and the apparent structural discordance between the Michigamme Formation and the Hemlock volcanic pile as pointed out by Foose (1980).

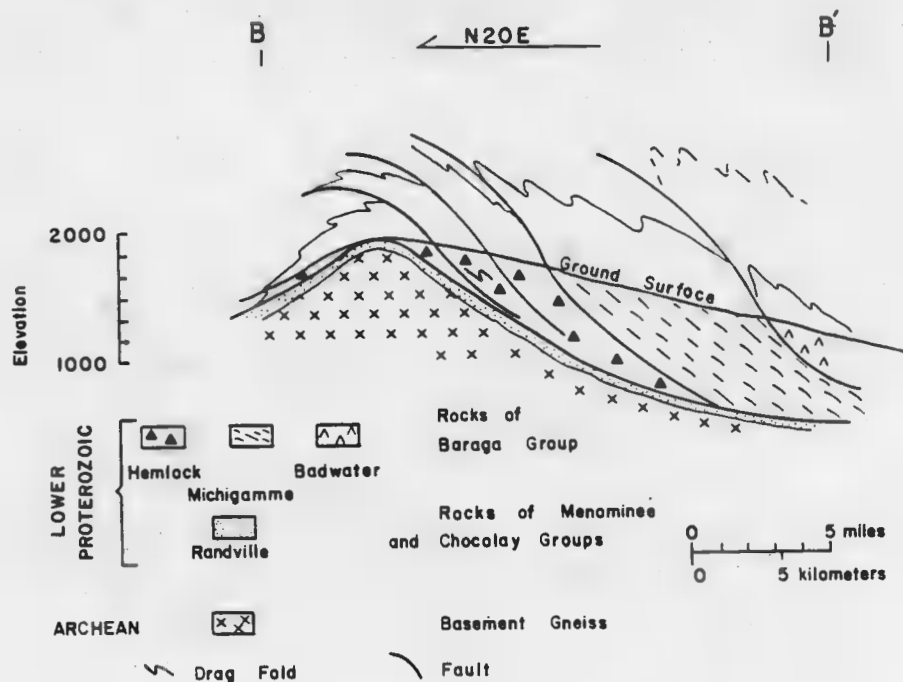


FIGURE 8. Structural profile B-B'. Note drag fold from stop 7b. Roughly 20 times vertical exaggeration. See Figure 3 for location.

In particular, either system would explain the structural discordance between the Hemlock and the magnetically mapped iron formation that lies just above the contact in the Michigamme Formation. We interpret the Michigamme Formation to be separated from the Hemlock Formation by a thrust fault. The configuration of the magnetically mapped iron formation mimics the configuration of the thrust fault. Inasmuch as the western edge of the Hemlock volcanic pile is covered, this fault is inferred and was not observed in the field.

The rocks that lie in the region between the Bush Lake fault and the Niagara fault (Fig. 3) are part of the north-verging thrust system described above, but the exact nature of the thrusting in this region remains problematic. Maharidge's (1986) interpretation that the Felch trough is part of a nappe structure has not been proven, but, also, it cannot be discounted at this time. Our recent studies show that both Archean and Early Proterozoic rocks possess a prominent low-dipping foliation that is superimposed upon a steeply-dipping foliation in the Archean rocks (see field stops 10 and 11). Also, in this region there is firm evidence for southwest verging thrusting in rocks of both the Felch and Calumet troughs. We tentatively interpret the south-verging structure as being formed due to south-directed backthrusting caused by ramping of the north-verging thrust faults. Best evidence for this southward vergence is found at stops 9, 11, 12, and 13. We will visit stops 9, 11, and 12 but we will most likely not visit stop 13, an alternate stop, because of difficult access.

A composite section (Fig. 9) along the length of the structural traverse summarizes our current, and as yet, tentative, interpretation of the style of deformation that occurred in northern Michigan. This interpretation is consistent with a foreland thrust system as depicted in the model of an idealized orogen by Hatcher and Williams (1986). The idealized orogen consists of a foreland overthrust belt, an overthrust metamorphic core complex that may include ophiolites and thrust crystalline basement rocks, and an accreted plutonic/volcanic terrane. Part A-A' of the composite section marks the foreland overthrust belt which involves thin-skinned tectonism with relatively little involvement of basement rocks in the thrusting (note these comments apply to the area close to this traverse, and the amount of basement involvement in Early Proterozoic overthrusting may change along the strike of the Penokean orogen). Telescoped and foreshortened Early Proterozoic strata are separated from basement rocks along a basal detachment fault. Nd isotope studies by Barovich and others, (1987) indicate that the southern half of this terrane was derived from the Wisconsin magmatic terrane to the south, thus supporting the idea of northward tectonic transport of at least a part the Michigamme Formation, and explaining the presence of deep water turbidite deposits on the continental margin.

Section B-B' marks the Amasa uplift area, which is transitional between thick-skinned basement-involved deformation

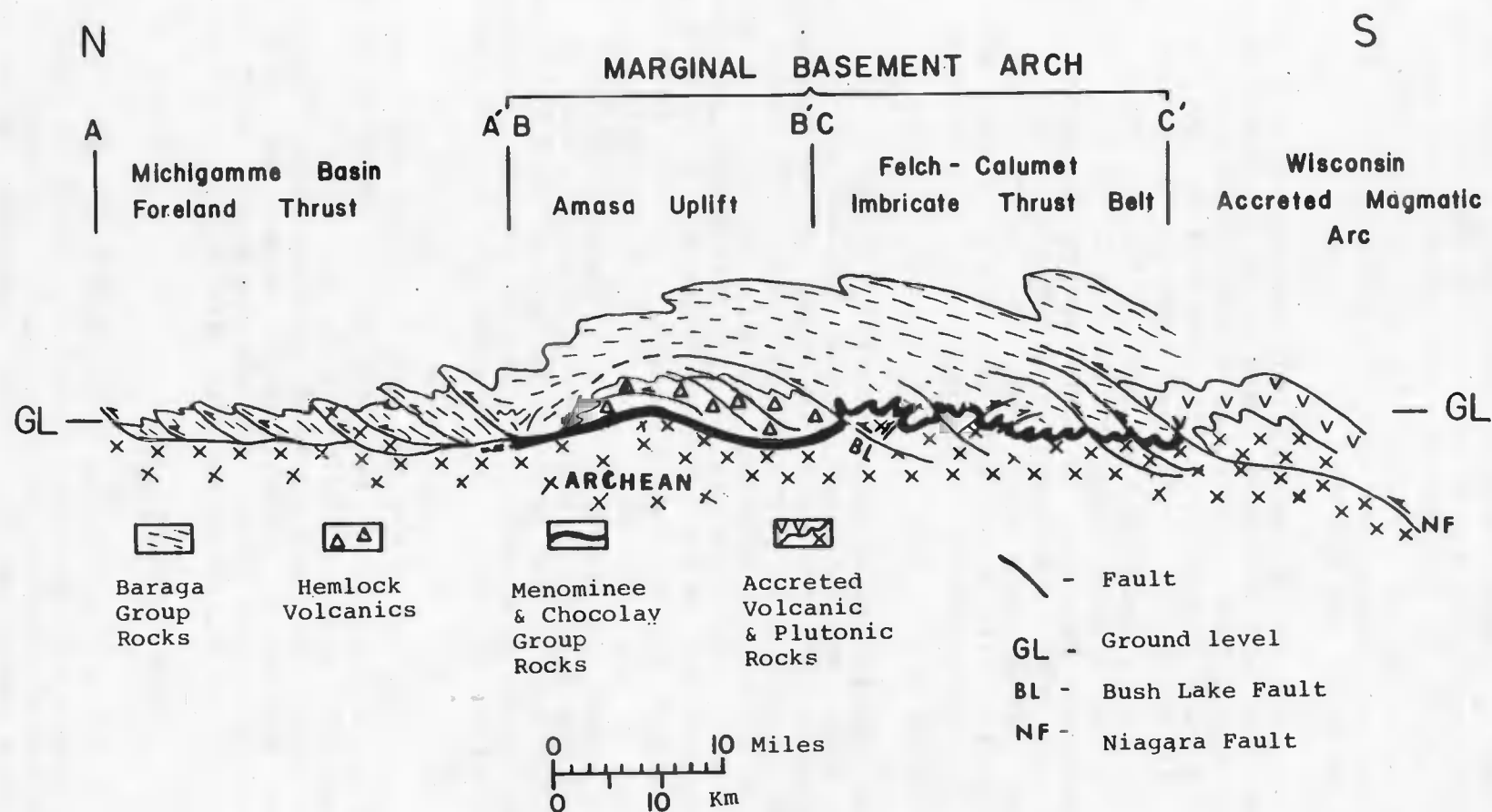


FIGURE 9. Composite structural profile along line connecting A to C' on Figure 3. See text for discussion.

to the south near the continental margin, and the thin-skinned tectonism of the foreland thrust belt to the north. Tentatively, we consider the Amasa uplift as having behaved as a stable block consisting of an Archean core and a large volcanic pile over which less competent rocks of the continental margin were thrust. The thrust system refracted upward from the Archean basement on the south so that it is largely confined to supracrustal Early Proterozoic strata north of the uplift.

Part C-C' on Figure 9 marks the crystalline metamorphic core complex system of Hatcher and Williams (1986). It consists of an imbricate, piggy back-type of crystalline thrust sheet which is bounded on the south by the Niagara fault zone and on the north by the Bush Lake Fault (Fig. 3). The Bush Lake Fault appears to have been a key feature in evolution of the thrust system. It marks a boundary between structures on the north which trend northwest and those on the south which trend east-west (see Fig. 3). Metamorphic isograds (Attoh and Vander Muelen, 1984 and Klasner and Attoh, 1986) indicate that the south side is upthrown. We interpret it to be a major fault along which crystalline rocks of the continental margin were thrust upward and over the Amasa uplift.

Rocks of the Wisconsin magmatic terrane, south of the Niagara fault zone, have been accreted to the continental margin. Nd isotope data indicate that the volcanic rocks of the magmatic terrane represent new Early Proterozoic crustal material (Barovich and others, 1987). Klasner and Osterfeld (1984) and Sims and others (1984b, 1985) suggested that the magmatic rocks of northeast Wisconsin are, in part, allochthonous. Klasner and others (1985, page 284) and Klasner and Attoh (1986) inferred that the actual edge of the continental margin is cryptic, and possibly buried beneath the allochthonous magmatic terrane in northern Wisconsin. The Wisconsin magmatic terrane is equivalent to the accreted volcanic/plutonic terrane of Hatcher and Williams (1986), which can contain slivers of oceanic crust. Schulz (1987b) has identified an ophiolite assemblage in northeast Wisconsin.

The geology of the Early Proterozoic continental margin assemblage of northern Michigan is consistent with younger Atlantic-type (passive) margins (Nelson and others, 1982) as represented in the Ouachitas, New England Appalachians, Tibetan Himalayas, and Oman Mountains. They have in common an inboard, allochthonous foreland thrust belt, and an outboard imbricate thrust system involving crystalline basement rocks.

AGE OF THRUSTING

A minimum age for the overthrusting is 1824 ± 2.6 Ma, which is a U-Pb zircon intercept age on an undeformed granite pluton that intrudes Badwater Greenstone at locality A on Figure 5 (Z. E. Peterman, written communication, 1987). A possible maximum age is 1929 ± 17 Ma; two splits of apatite from iron formation underlying the Michigamme Formation in the Baraga basin yield

lead-lead ages of 1929 ± 17 Ma (R. E. Zartman, written communication, 1987). The thrusting occurred within the interval 1930 to 1824 Ma. Data from northeastern Wisconsin, within the Wisconsin magmatic terrane, is consistent with these constraints and further refine the age limits. In the Dunbar dome, deformed granitoid rocks have U-Pb zircon ages of ca 1860 Ma, whereas an undeformed, post-tectonic granite has an age of 1835 ± 6 Ma (Sims and others, 1985). These data suggest collision along the Niagara fault zone occurred about 1850 Ma. Probably the thrusting in the continental margin assemblage occurred approximately contemporaneous with or slightly later than collision.

FIELD STOPS AND ROAD LOG

The structural traverse across northern Michigan starts in L'Anse, Michigan and ends near Florence, Wisconsin. Eighteen stops are shown on Figure 3 but, because of limited time and difficult access to several of the localities, only eight to ten of them will be visited. Localities 2b, 7a, and 7b, will not be visited and localities 2a, 8, and 13 are alternate stops, which will be visited only if time permits. Road logs are not given for the alternate stops, but their location is given by section, township, and range.

ROAD LOG Follow highway U. S. 41 west from Marquette to L'Anse. Proceed west through L'Anse to bridge over Falls River on U. S. 41. Park in the pull-off area on the north side of the highway between the RR tracks and the bridge.

STOP 1-FALLS RIVER. Numerous outcrops are present along Falls River on both sides of the highway. Structures consist of northward-verging, small-scale, recumbent folds with subhorizontal axial-plane foliation indicating nappe-thrust style of deformation in this area.

ROAD LOG. From the parking lot area for stop 1, follow U. S. 41 east for 2.6 miles. Turn west on Golf Course Road and drive 1.75 miles to the cul-de-sac at the end of the road. Follow footpath to Little Mountain. It is about a 15 minute walk to the top of the mountain; be sure to follow left forks of the main, well worn path. Path extends around the southwest corner of the mountain where it turns sharply toward the east up the south flank of the mountain. Follow path to the highest point on the mountain. From this vantage you can see the Keweenaw Peninsula of the Midcontinent Rift System to the north-northwest and the Archean terrane of the northern complex (Fig. 3) to the east-southeast. The low lying area to the south is underlain by rocks of the Michigamme basin.

STOP 2-LITTLE MOUNTAIN. Outcrops at the highest point on Little Mountain consist of an unfoliated (ca 1.1 Ga) Keweenaw diabase dike and graded beds of metagraywacke. Grading is expressed by presence of foliation in the finer grained bed tops. The beds face toward the north and dip steeply south, indicating that they are overturned toward the north.

LITTLE MOUNTAIN, BARAGA COUNTY, MI.

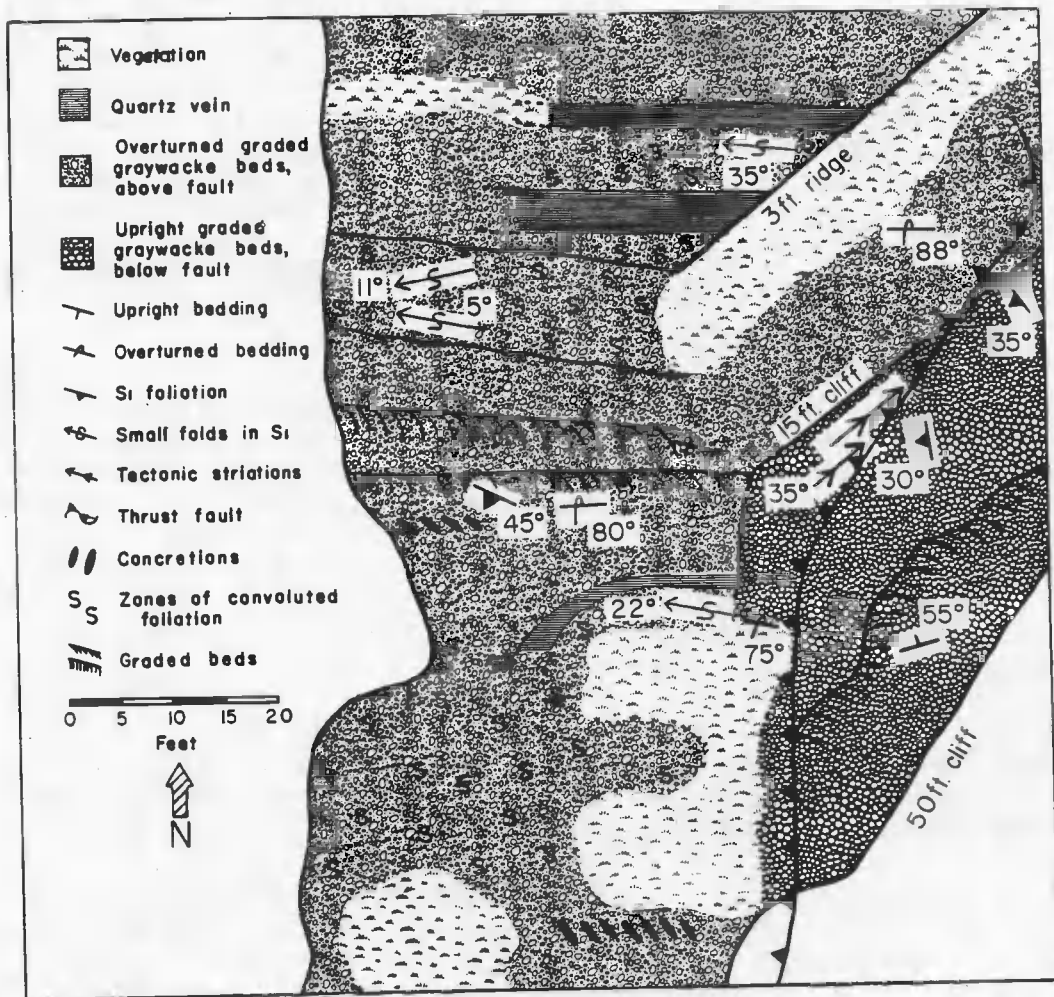


FIGURE 10. Field sketch map of the northeast corner of Little Mountain showing evidence for thrust faulting.

Figure 10, a sketch map, shows the nature of structural deformation near the northeast corner of Little Mountain. Here, similar overturned graded beds of metagraywacke strike east-west and dip steeply south, as does S₁ foliation. In several places bedding has a convoluted appearance, indicative of intense deformation. Deformed zones of concretions crudely define bedding. The long axes of the concretions plunge steeply southwest, indicating extension in this direction. Fold axes plunge gently toward the west. On a bench at the easternmost edge of the mountain similar graded beds are oriented N60° W.

57°NW, and are upright. Looking west from the bench, the intensely deformed beds of an overlying thrust can be seen in the three-meter-high cliff. Tectonic striations can be found on the underside of narrow overhangs on the cliff face a few meters to the north and west. The striations, along with northward overturning of bedding indicate that the hanging wall of the thrust moved northeastward. The total thickness of the thrust fault zone at this locality is a meter or less. The thrust fault can be traced down the east flank of Little Mountain. About 100 meters south and two benches down the flank of the mountain a glacially-gouged, upright bed of metagraywacke which lies beneath the fault observed above is well exposed. It too has deformed concretions whose long axes plunge southwest.

The main point at this stop is that Little Mountain probably is an erosional remnant of an allochthonous sheet of rocks that has been thrust northeastward as part of an imbricate thrust system. Further studies at Little Mountain are needed to fully document the nature and style of deformation here.

ROAD LOG Return to the vehicle by walking north and west around the north side of Little Mountain to the intersection of the path. Turn right (east) on the path and return to Golf Course Road. Follow the road eastward to the intersection of Golf Course Road and U. S. 41. Turn right (south) on U. S. 41.

ALTERNATE STOP 2a-TAYLOR MINE. Located in the NW 1/4 sec. 9, T49N, R33W, graphitic slate and iron-formation of the Michigamme Formation near the mine have been folded about a penetrative south-dipping, axial-plane foliation (see Fig. 7). Keels of rootless folds in the graphitic slate indicate that bedding has been transposed parallel to foliation, and that the beds are overturned to the north. An unfoliated Keweenaw diabase dike cuts the graphitic slate. Style of folding in the iron-formation can be seen in a roadcut about 30 meters north of the dike.

Similar steeply south-dipping foliation occurs in Early Proterozoic phyllite about 2 km to the south at Plumbago Creek (2b, Fig. 3). The phyllite is exposed in a creek bed at the base of a steep north facing slope that is underlain by Archean gneiss. Thus, it appears that the foliation in the phyllite dips beneath the gneiss, suggesting that the gneiss is thrust over the phyllite.

ROAD LOG. From the intersection of Golf Course Road and U. S. 41 drive 7.6 mile south on U. S. 41 to Canyon Falls Park. Between Alberta on U. S. 41 and Canyon Falls Park the highway passes over the west end of the northern complex (Fig. 3) which is an uplifted block of Archean basement rock. Follow the nature path from the parking lot at Canyon Falls Park westward for about 10 minutes along Sturgeon River to the Falls. Proceed to the north-south oriented cliff face in back of the fence. No need to walk up the steps in the cliff face for the critical information at this stop is visible in the cliff face.

STOP 3-CANYON FALLS. At this stop subhorizontal Early Proterozoic quartzite contains prominent interference ripples that appear to be unaffected by Early Proterozoic deformation. Close examination of the cliff face, however, reveals that thin pelitic layers intercalated between the quartzite beds have a penetrative foliation oriented $N85^{\circ}W$, $27^{\circ}SW$. Also, tectonic striations on the quartzite beds are oriented 2° toward $N10^{\circ}E$. Clearly the quartzite has been transported some unknown distance northeastward (based on the north sense of vergence found in previous outcrops). Deformation was taken up by the less competent shaly layers; the more competent quartzite beds appear to have undergone little, or no, internal deformation, but detailed petrofabric studies are needed to confirm this.

As shown on Figure 6, the flat-lying quartzite at Canyon Falls must lie beneath one or more thrust faults that intensely deformed Early Proterozoic strata at Taylor Mine and Plumbago Creek. Also, elevation data, together with structural data at these three localities necessitate local involvement of Archean basement rocks in the overthrusting.

ROAD LOG Return to Canyon Falls Park parking lot. Drive south on U. S. 41 for 3.0 miles to the intersection with highway U. S. 141/28. Turn right (west) on highway 141/28 and follow it for 4.1 miles. Turn south on U. S. 141 and drive 4.1 miles to stop 4.

Numerous outcrops of the upper slate member of the Michigamme Formation occur along U. S. 141 south of Covington. We have selected a few of the more informative outcrops as field stops (4, 5, 6, and 7 on Figure 6).

STOP 4-U. S. highway 141. Located on the east side of the highway, this stop consists of thick beds of graywacke that are graded and have flame structures at some bed contacts. Penetrative foliation refracts across bedding. Bedding (S0) is generally oriented $N62^{\circ}W$, $20^{\circ}SW$, and cleavage (S1) $N75^{\circ}W$, $40^{\circ}SW$. Lineations, formed by the intersection of cleavage and bedding plunge 14° toward $S83^{\circ}W$. Numerous concretions form strain ellipses with the axes of maximum elongation that plunge generally 54° toward $S36^{\circ}E$.

At this outcrop bedding (S0) dips only moderately toward the south, but marked variations in the orientation of bedding as well as cleavage (S1) can be seen in other outcrops as one proceeds south along U. S. highway 141. We mainly used these variations in structure to locate the position of thrust faults shown on Figure 6.

ROAD LOG. Proceed south on U. S. 141 for 2.4 miles.

STOP 5-U. S. 141. A long outcrop of thick-bedded graywacke is present on the west side of the highway. Graded beds strike roughly $N67^{\circ}W$, and are nearly vertical; foliation is subparallel

to bedding. At the north end of the outcrop bedding is clearly overturned toward the north.

ROAD LOG Proceed south on U. S. 141 for 3.4 miles.

STOP 6-TRACY CREEK. Examine outcrops on both sides of the highway which consist of graded graywacke beds. Folds in bedding (S0) have axes that plunge gently toward the northwest. Refracted, penetrative S1 foliation is oriented N86° E, 85° SE. Concretions tend to lie in the bedding plane. Some concretions, however, have been partly transposed so that their long axes are partly parallel to bedding and partly parallel to foliation. Many have been deformed so that their long axes are completely parallel to foliation. This outcrop shows the style of deformation in the slates and metagraywackes of the Michigamme Formation. Some outcrops on this part of the U. S. 141 traverse have two foliations as shown on Figure 6. A completely different, north dipping foliation will be seen at the next stop.

ROAD LOG. Proceed south on U. S. 141 for 1.0 mile.

STOP 7-U. S. 141. Most features in this long outcrop of black slate and metagraywacke on the east side of the highway indicate a southward sense of thrusting, completely opposite to that observed at all previous stops. Figure 11 is a sketch illustrating the types of features observed along the length of the outcrop. Most significant are points 5 and 9. At point 5 small drag folds indicate a southward sense of vergence. This southward sense of vergence is confirmed by several other features in this outcrop and indicates backthrusting at this location. A meter-wide zone of sigmoidal quartz veins at point 9 is one of the more striking features in this outcrop. The sigmoidal shape of the quartz veins suggests down-to-the-north normal faulting, opposite the sense of movement observed at point 5. The structure at point 9 may be a late feature related to post-thrusting uplift of the Amasa dome. Such uplift would cause rotation of pre-existing features, but the amount of rotation is not known.

We interpret the backthrusting at this locality to be caused by an abrupt change in dip of the thrust system as it ramps off the north edge of the Amasa uplift (see Fig. 6).

ROAD LOG. Proceed south on U. S. 141 for a distance of 23 miles to the junction of U. S. 141 with U. S. highway 2 at the west end of Crystal Falls, Michigan. On this segment of the traverse, the highway passes over the west flank of the Amasa uplift. Turn left (east) on U. S. 141/2 and follow it to the center of Crystal Falls, where the highway intersects M 69. This is at the intersection of Superior and Fifth street, near the U. S. Post Office in Crystal Falls. To proceed to alternate stop 8, turn east on M 69. To continue on to stop 9 proceed south on U. S. 2/141.

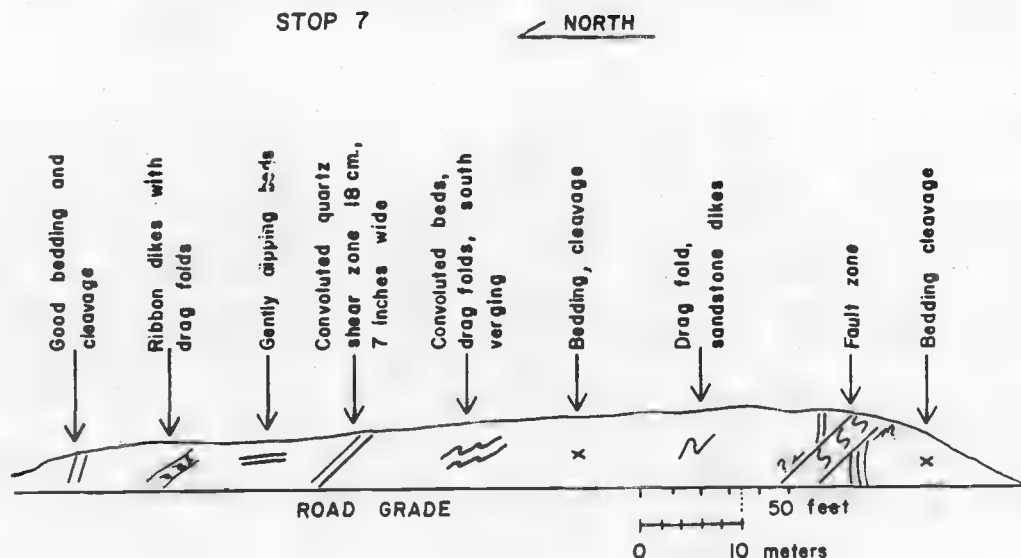


FIGURE 11. Sketch of roadcut at stop 7, east side of road, showing location and attitude of some key structural features.

ALTERNATE STOP 3-OLD M69. This stop is located in the NW 1/4, sec. 20, T43N, R31W, about 500 meters east of the bridge over the Michigamme River on Old M 69. Here thinly layered tuff, oriented N20°W, 50°SW, has a penetrative S1 foliation oriented N65°W, 79°SW. This northwest-trending foliation is characteristic of the structural fabric in the region (west side of the Amasa uplift), as shown on Figure 3.

ROAD LOG. To reach stop 9 from the center of Crystal Falls, proceed south on U. S. 2/141 for roughly 6 miles, to the road on the east to Horse Race Rapids and Iron County Airport. Turn left (east) and follow this road for 3.5 miles to parking area at Horse Race Rapids. Follow path down slope to plentiful outcrops along the river.

STOP 9-HORSE RACE RAPIDS. This outcrop area is south of Bush Lake Fault (see Fig. 3). At this locality graded beds (S0) of graywacke stratigraphically face south, and form a system of folds that have a subhorizontal axial-plane foliation (S1). Fold axes in S0 plunge gently westward. S1 foliation has been refolded in some places on fold axes that are nearly coaxial with the fold axes in S0. Syntectonic quartz veins occur in the axes

of some folds. We interpret this outcrop to be part of the south-verging backthrust system, the same as that found in the Felch Trough-Calumet trough area (see Fig. 3).

ROAD LOG. Return to the intersection of the Horse Race Rapids road with U. S. highway 2/141. Turn left onto U. S. 2/141 and proceed east for 18.9 miles to the intersection with M 95. Turn left (north) on M 95 and follow 10.2 miles to the intersection with County Road 569 which goes eastward to Felch, MI. Follow CO 569 east through Felch for 14.9 miles to stop 10 (about 1.5 miles west of the village of Foster City).

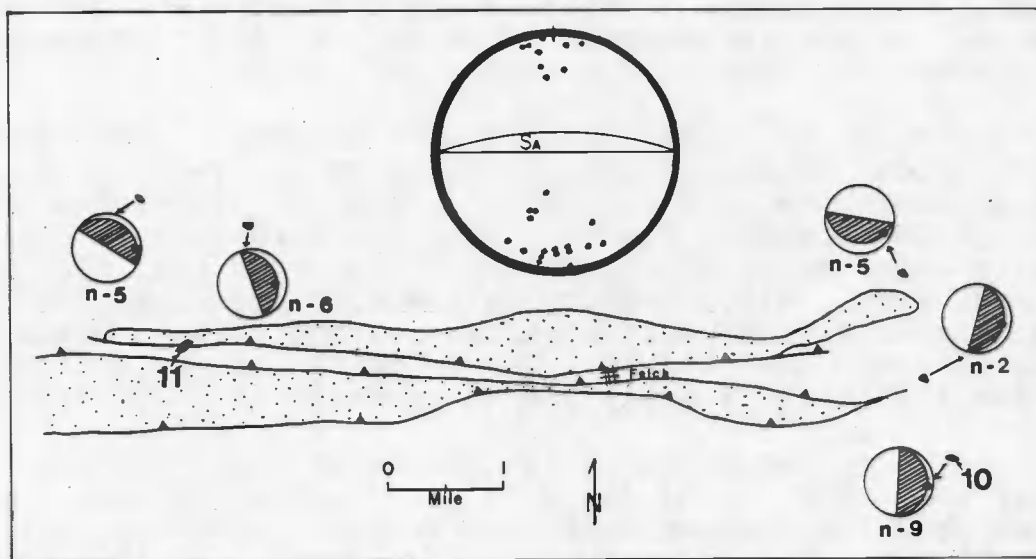


FIGURE 12. Map of east end of Felch trough (adapted from James and others, 1961) showing locations of stops 10 and 11. Small lower hemisphere stereoplots show orientation of low-dipping S_1 foliation; large lower hemisphere stereoplot shows steep (S_a) foliation in Archean gneiss. Black dots in the stereoplots show orientation of lineation formed by the intersection of S_a and S_1 . Black dots outside the stereoplots show location of outcrops.

STOP 10-CO 569. Granitoid gneiss on the north side of the road has two distinct foliations. The steeper foliation, herein called Sa, is an Archean fabric that strikes about N85°W, and dips nearly vertical (see large stereoplot on Fig. 12). A sub-horizontal foliation (S1), expressed by aligned zones and clots of biotite, is oriented about N10°W, 25°NE. Gneissic foliation and fold axes in gneissic foliation in Archean rocks throughout the Felch trough region are steep. The nearly flat lying penetrative S1 foliation is found throughout the Felch trough area, as shown on Figure 12, but because the Archean fabric (Sa) is generally more prominent, it is difficult to recognize S1 (for example, climb to the large outcrop area in back of the roadcut and look for S1 on this nearly horizontal surface). The small stereoplots on Figure 12 shows that the S1 foliation is irregular in orientation. The next stop shows that S1 also exists in Early Proterozoic rocks.

ROAD LOG. Turn around at stop 10 and proceed west on CO 569 for 6.7 miles to the intersection with Old M 69. Proceed south (left) on M69 for only 0.25 miles to the bridge.

STOP 11-OLD M 69. Figure 13A is a geologic map showing a sequence from north to south of roughly vertically bedded Sturgeon Quartzite and Randville Dolomite sandwiched between Archean gneiss blocks. The fact that the stratigraphically older quartzite lies north of the dolomite indicates that the section faces southward. Also, bedding in the dolomite on the north side of the river dips steeply north suggesting slight overturn of bedding toward the south. The dolomite has a subhorizontal foliation (S1) that is axial planar to small folds in it.

There are two distinct foliations in the Archean gneiss south of the river. The steep dipping Archean foliation (Sa) is crosscut by low-dipping Early Proterozoic foliation (S1), the same subhorizontal foliation as is found in the Randville Dolomite, but note that the dolomite does not have a steep foliation.

Our interpretation of the structure at stop 11 is shown in cross section A-A' (Fig. 13a). We suggest that the Archean gneiss has been thrust above the Sturgeon Quartzite and Randville Dolomite, which are exposed as a window in the Archean thrust sheet. Southward facing stratigraphy indicates southward vergence in the thrust system. The thrusting created the S1 subhorizontal foliation in both Early Proterozoic and Archean rocks, but the steep Sa fabric occurs only in the Archean gneiss.

Figure 13B shows the thrust system in a broader perspective, and provides additional key evidence for southward vergence in the Felch trough area. Although the exact configuration of the thrust faults is not known at this time, the drag fold which occurs in Sturgeon Quartzite, as diagrammatically shown on cross section B-B', unequivocally indicate southward vergence. The drag fold actually occurs about a mile west of the profile at the same structural position along the fault. We will not see it

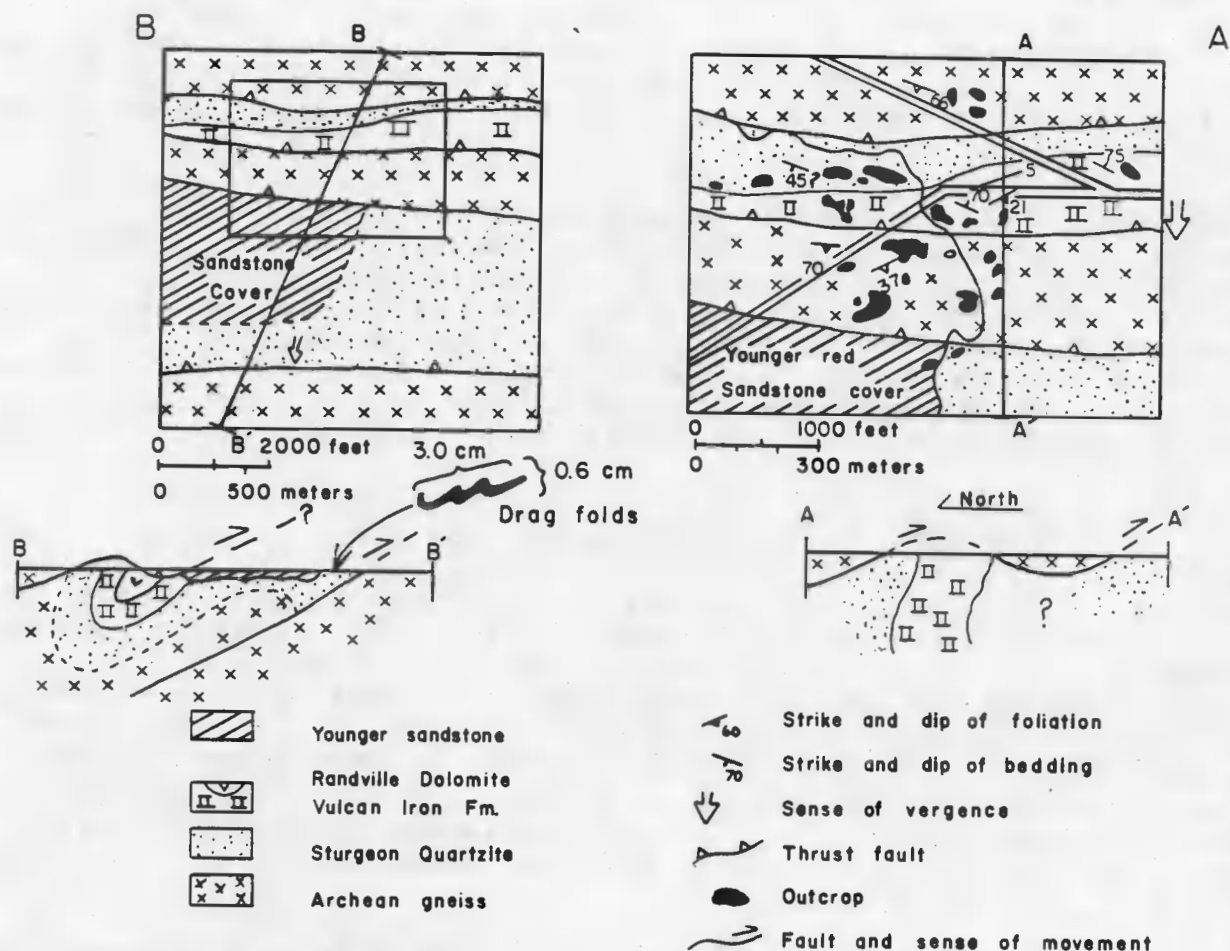


FIGURE 13. Geologic maps in area of stop 11 (adapted from James and others, 1961). Map A and geologic cross section shows the structural relationship between Archean gneiss and Early Proterozoic Sturgeon Quartzite and Randville Dolomite. Map B and structural cross section is of a larger area (note location of map A and drag fold). These maps show that low-dipping foliation (S1) occurs in both Archean and Early Proterozoic rocks, whereas the steeper foliation (S2) occurs only in the Archean gneiss. The maps and cross sections also present evidence for southward structural vergence. See text for further discussion.

because of difficult access to the outcrops.

In summary, several key points can be made from this stop:
1) S_a fabric is found only in Archean rocks (and not in Early Proterozoic rocks), thereby proving an Archean age for S_a.
2) Sub-horizontal S₁ fabric is found in both Archean and Early Proterozoic rocks, thereby proving that it is not older than Early Proterozoic age.
3) Thrust vergence is toward the south in the Felch trough area.

ROAD LOG. Turn around and return to intersection of Old 69 and CO 569 (a distance of 0.25 miles). Turn left (west) on 569 and follow it for 8.2 miles to intersection with M 95. Turn left (south) on M 95 and follow it for 5.4 miles to Steele Road (Swanson Road on right). Turn left on Steele Road and follow it to "THE STEELE FARM" at end of road. After checking with residents, go through gate to field on the east. Outcrops are in the southern part of the field about 400 m east of the farmhouse.

STOP 12-STEELE FARM. This outcrop of Michigamme Formation is in the Calumet Trough (Fig. 3). Here graded beds (S₀) of metagraywacke, now quartz-sericite-biotite schist, have a prominent subhorizontal foliation (S₁) that refracts across bedding. S₁ is oriented roughly N90°E, 25°SE, and is axial planar to folds in the metagraywacke that plunge gently northwest. Bedding strikes roughly east and dips steeply south. Graded beds and flame structures in the metagraywacke indicate that stratigraphic facing is toward the south. Both S₀ and S₁ have been refolded with a steeper foliation (S₂) that strikes approximately N40°E. Also, crinkle folds on the S₁ surfaces indicate post-F₁ folding.

In summary, this outcrop indicates that there is a prominent subhorizontal foliation in Michigamme strata in the Calumet trough. Sedimentary structures indicate that bedding faces toward the south. This implies that S₀ has been rotated toward the south and that the Calumet trough is a south-verging structure.

ROAD LOG. Return to M 95 and turn left (south). The turn to alternate stop 13 is 1.0 mile south of Steele Road on M 95 at the intersection of M 95 with Sportsman Club Road. Turn left (east) on Sportsman Club Road.

ALTERNATE STOP 13. This is a large outcrop area of the Michigamme Formation in the Calumet trough located in the E1/2, sec 21, T41N, R28W at a sharp bend in the Sturgeon River. The rocks here are metagraywacke, now schist and phyllite. They have a subhorizontal foliation (S₁) which is axial planar to numerous drag folds in bedding (S₀), which indicate south vergence. S₁ foliation forms a gently undulating surface which, in places, has been folded with an S₂ axial plane that strikes northwest and is steeply dipping. Like the strata at stop 12, this outcrop also shows that the Calumet trough is a south verging structure.

ROAD LOG. To reach stop 14 from the intersection of Steele Road and M 95, proceed south on M 95 for a distance of 4.8 miles to the intersection with U. S. 2/141. Turn right and proceed west on U. S. 2/141 for approximately 11 miles to the center of the town of Florence, Wisconsin. Turn left (south) on County Road N in the center of Florence and proceed south for 3.3 miles to the intersection with County Road D. Turn right on CO D and go 1.3 miles west to a gravel road labelled "Site 34". Follow this road for 3.4 miles to the Pine River dam. From the parking lot near the dam walk onto the dam embankment to a chain link fence that blocks access to the discharge flume from the dam. Turn left and walk down the embankment next to the chain link fence for about 400 feet (130) meters to outcrops along the river.

STOP 14-PINE RIVER FLOWAGE. This outcrop lies within the Niagara fault zone. The rocks here consist of strongly foliated chloritic-garnetiferous schist. Primary layering has been transposed parallel to S1 foliation. Dextral drag folds in the transposed layering have steeply plunging axes, which are parallel to mineral lineations on the foliation surfaces. Axes of maximum elongation in deformed concretions plunge 60° toward S80°W, parallel to the mineral lineation.

The deformation shown in this outcrop is completely different from that seen in the previous outcrops. A subhorizontal foliation is lacking as is any evidence for a southward structural vergence. Rather, these highly strained rocks have an S1 foliation that dips steeply south, as do the elongation (stretching) axes. As defined by Ueng and others (1984), this stop lies within the Florence-Niagara terrane, which is characterized by a west-northwest-trending, steeply south-dipping foliation that contains a prominent south-plunging stretch lineation. Similarly oriented structures occur in volcanic rocks of the Wisconsin magmatic terrane on the south margin of the Niagara fault zone, a few miles south of the Pine River dam (Sims and others, 1985). The structural fabric in this region reflects overthrusting of the Wisconsin magmatic terrane from the southeast onto the continental margin.

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