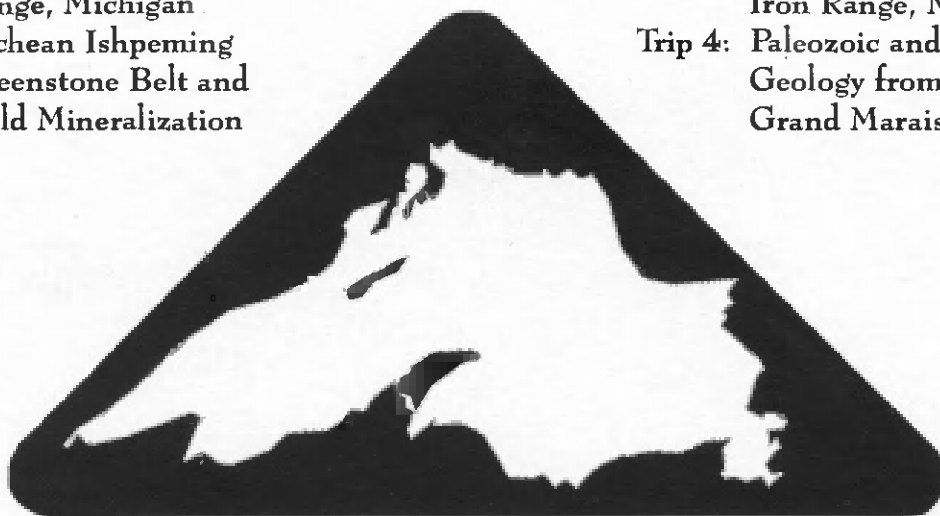


Trip 1: Early Proterozoic Strata
of the Marquette Iron
Range, Michigan

Trip 2: Archean Ishpeming
Greenstone Belt and
Gold Mineralization

Trip 3: Tilden and Empire
Mines of the Marquette
Iron Range, Michigan

Trip 4: Paleozoic and Glacial
Geology from Au Train to
Grand Marais, Michigan



Institute on Lake Superior Geology

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Marquette, Michigan

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Proceedings Volume 45:
Field Trip Guidebook
Theodore J. Bornhorst, editor

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INSTITUTE ON LAKE SUPERIOR GEOLOGY

PROCEEDINGS

Volume 45

Part 2: Field Trip Guidebook

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Field Trip 1

Early Proterozoic Strata of the Marquette Iron Range, Michigan

Leader: W.F. Cannon

FIELD TRIP #1

EARLY PROTEROZOIC STRATA OF THE MARQUETTE IRON RANGE

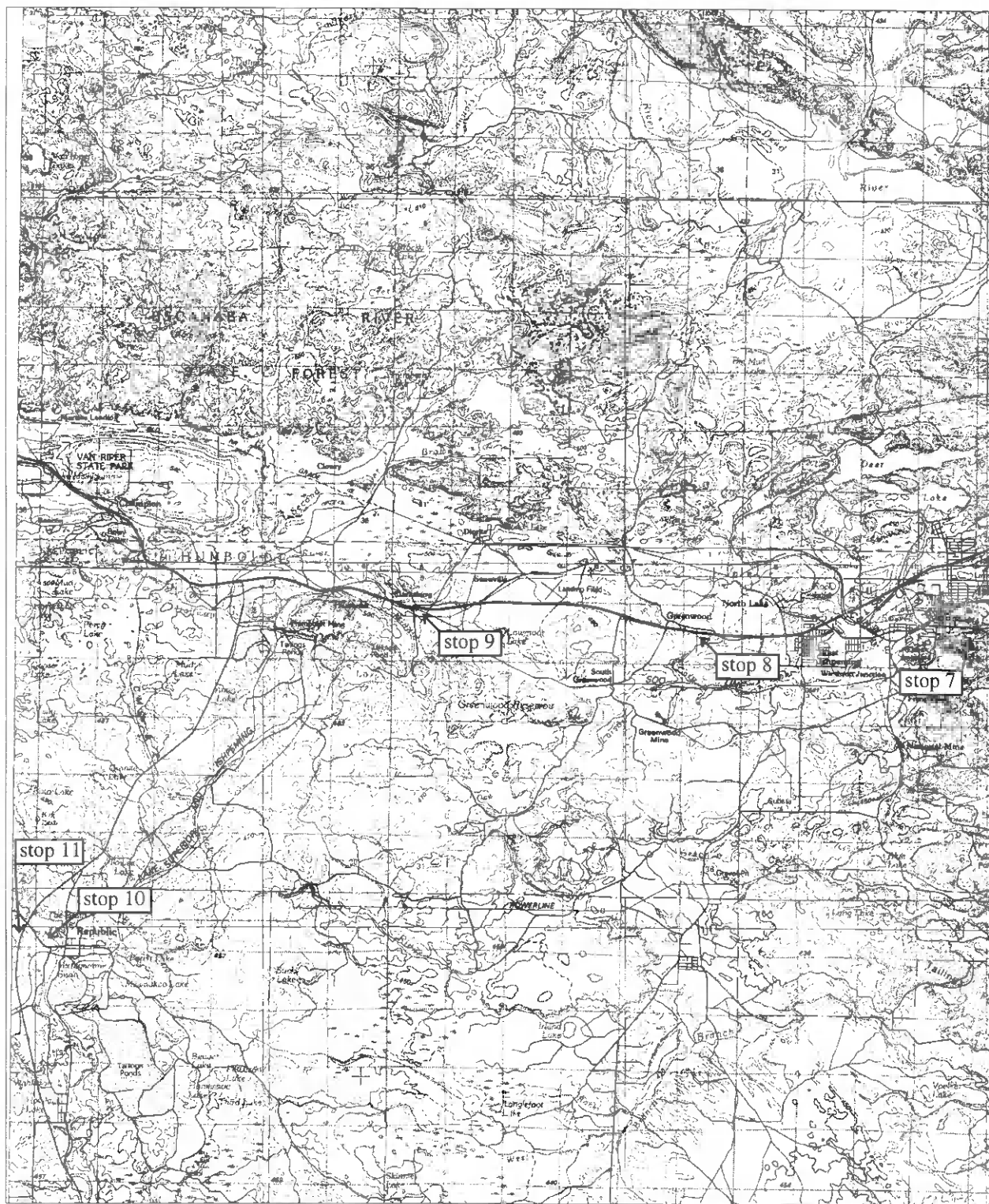
LEADER: W.F. CANNON, U.S. GEOLOGICAL SURVEY

INTRODUCTION

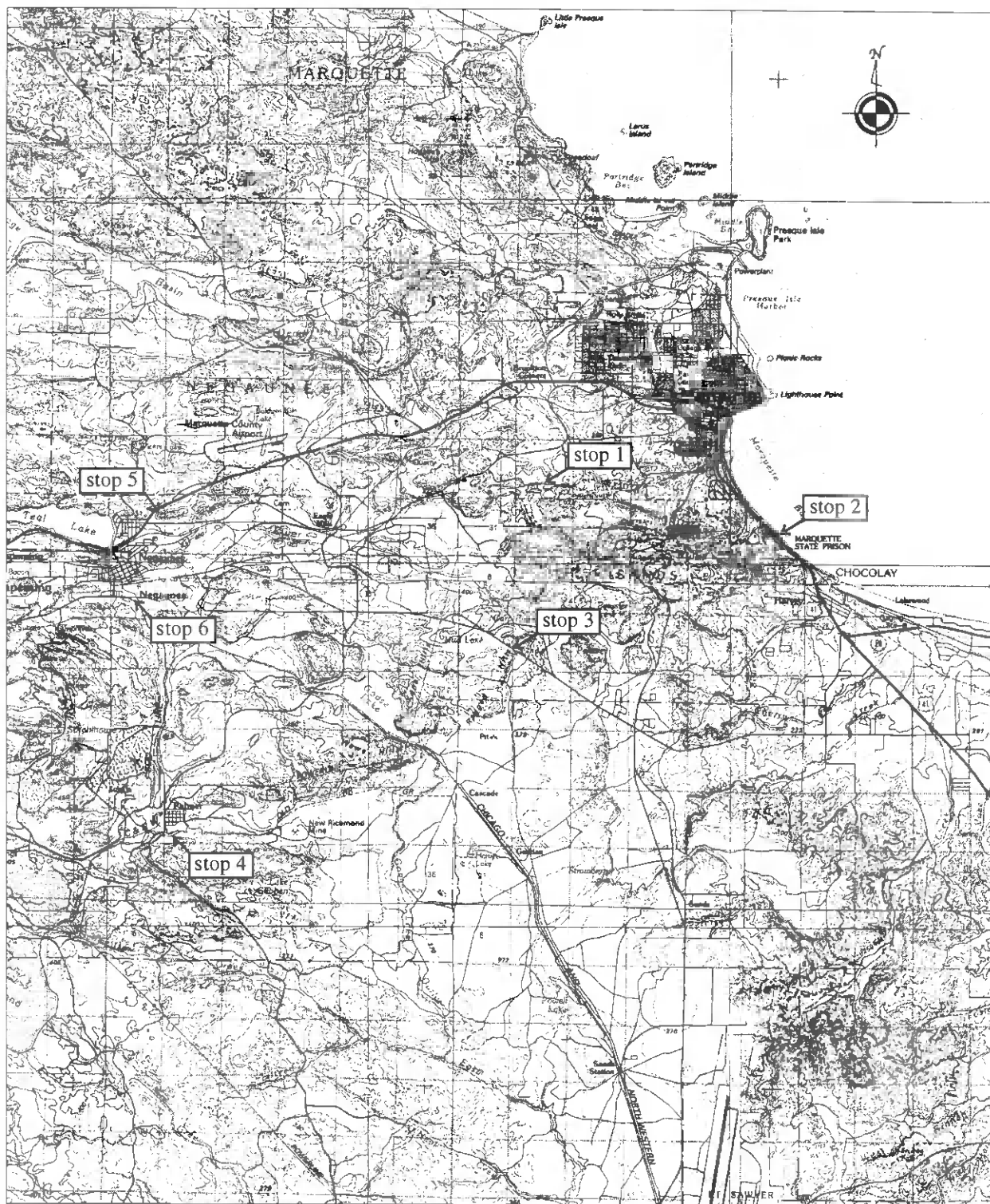
Early Proterozoic strata of the Marquette Range Supergroup preserved in the Marquette Iron Range record the tectonic evolution of a continental margin along the south edge of the Archean Superior craton. That evolution spans an imprecisely known period culminating in suturing with volcanic arcs to the south at about 1855 Ma. Lower parts of the section, the Chocolay Group (Stops 1, 2, 3, 5), are mostly a sequence of pure quartzite, dolomite, and shale believed to have formed in a stable cratonic setting. They were deposited unconformably on Archean greenstone and granite, but the contact is now most commonly a fault (Stop 1). A low angle unconformity separates the Chocolay Group from the overlying Menominee Group (Stop 5). The Menominee Group consists of a basal quartzite-shale unit (Stop 5) overlain by the principal iron-producing unit in the range, the Negaunee Iron-formation (Stops 6, 7, 10). The Menominee Group was deposited in actively subsiding grabens, probably on the rifting continental margin, although a foreland basin setting is possible and is favored by some current researchers in the region. Strata of the Baraga Group (Stops 4, 8, 9, 11) are widely accepted as products of sedimentation in a foreland basin during accretion of volcanic terranes now preserved in northern Wisconsin. The Baraga Group which lies with a prominent low angle unconformity on rocks of the Menominee Group (Stop 4), is composed mostly of a turbidite sequence of graywacke and shale (stop 11), quartzite and conglomerate (stop 4), lesser black shale (stop 8), and minor volcanic rocks (stop 9).

The Marquette Iron Range is a complexly folded and faulted, gently west-plunging synclinorium composed of strata of the Marquette Range Supergroup and intrusive diabase sheets. Deformation occurred during the Penokean orogeny at about 1850 Ma. The synclinorium is bounded on both the north and south by Archean volcanic and granitic rocks, which are most commonly in fault contact with the Early Proterozoic strata. The intense penetrative deformation seen in the Early Proterozoic strata is not present in the Archean basement rocks, which were last penetratively deformed in Lake Archean time. This has led to the interpretation that the Archean rocks behaved as relatively rigid, fault-bounded blocks during the Penokean orogeny, and were structurally decoupled from the highly deformed Early Proterozoic strata. By that interpretation, the Marquette synclinorium is a graben with respect to Archean basement rocks. The synclinorium of Early Proterozoic rocks lies within that graben.

The Marquette area contains many classic geologic localities that have been visited by literally thousands of geologists during the past century. The Institute on Lake Superior Geology has visited the area during several past meetings, but the Marquette Range stratigraphy has not been examined since the Twenty-first Annual Meeting in 1975. This guidebook is based very largely on the guidebook prepared for that meeting and other guidebooks (Cannon and others, 1975; Prinz, and others, 1975; Margeson, 1989; Morey, 1989). For those who have toured the region before, the stops will be largely the same and the rocks familiar; only the interpretations have changed. The stops are arranged, to the extent practical, to view the stratigraphy beginning at the base of the section and progressing up-section. To streamline logistics and minimize driving distances a few stops are out of proper stratigraphic order.



0 1 2 3 4 5 miles



Stop 1. Enchantment Lake Formation and Archean volcanic rocks.

The Enchantment Lake Formation is a discontinuous unit at the base of the Marquette Range Supergroup. It consists of conglomerate, graywacke, arkose, and slate. Most geologists who have studied it believe that it is of glacial origin, although that interpretation remains in dispute. It conformably underlies the Mesnard Quartzite. The transition to the Mesnard can be seen in hills immediately south of stop 1, but will not be visited on this trip.

Immediately north of the Old State Road are several exposures of basal conglomerate of the Enchantment Lake Formation, containing fragments of tonalitic gneiss and greenstone. The matrix is rich in chlorite. The conglomerate can be seen in sharp vertical contact with slaty, highly sheared greenstone of the underlying Mona Schist (Archean). About 100 feet north of the contact, the Mona becomes mostly massive greenstone. Both the greenstone and conglomerate are strongly foliated near the contact and steeply plunging to vertical lineations are common on foliation surfaces.

The contact of the Mona Schist and Enchantment Lake Formation has been interpreted as a fault. In addition to the highly sheared rocks along the contact, the two units are stratigraphically "back to back". Pillows in the Mona Schist in nearby outcrops are uniformly north-facing, whereas the Enchantment Lake and overlying formations are south-facing. The present attitude of the rocks is probably a result of vertical rise of a fault block of Mona Schist and passive draping of the Enchantment Lake Formation over the block.

Stop 2. Mesnard Quartzite and Jacobsville Sandstone.

In this lakeshore outcrop the Mesnard Quartzite, the basal orthoquartzite unit of the Chocoday Group, is overlain with a sharp angular unconformity by the Middle Proterozoic Jacobsville Sandstone.

White-weathering vitreous Mesnard Quartzite in beds 4 to 8 inches thick strikes eastward and dips 80°S to vertically. Cross beds and ripple marks indicate top direction to the south, in conformance with the position of the quartzite on the north limb of the Marquette synclinorium. Reddish Jacobsville Sandstone dips 10-15° eastward to southeastward and the contact with the Mesnard is visible at several places on the outcrop. Patches of Jacobsville are plastered against the north side of the quartzite outcrop, and on the south side the contact is steep. Evidently during deposition of the Jacobsville, the Mesnard at this locality formed a low topographic ridge, much as it does now. Flat-lying Jacobsville is on the flank of Mt. Mesnard, about ¾ miles west of here and 370 feet above current lake level, which indicates a pre-Jacobsville topographic relief and ruggedness approximately the same or greater than that adjacent to the present shore of Lake Superior.

Stop 3. Kona Dolomite

The Kona Dolomite lies conformably on the Mesnard Quartzite. The formation is mostly dolomite, siliceous dolomite, and lesser amounts of fine- to medium-grained clastic rocks. The outcrops on the north side of the highway show exceptionally well preserved sedimentary textures indicative of a shallow water to intratidal environment, probably open tidal flats at this stratigraphic interval. Many beds are algal carbonates with large stromatolites exceptionally well displayed and accentuated by differential weathering. Please help preserve these features for future visitors. Other well preserved features include dessication structures, ripple marks, and rip-up beds probably produced by tidal currents.

Stop 4. Goodrich Quartzite

This stop, for the sake of economizing driving time, is not in proper stratigraphic order. We have temporarily skipped over the Menominee Group and will examine the basal conglomerate of the Baraga Group. At this stop, just south of the village of Palmer and near the old Isabella Mine, coarse conglomeratic rocks forming the lower part of the Goodrich Quartzite are exposed. The Goodrich Quartzite, the basal unit of the Baraga Group, unconformably overlies the Negaunee Iron-formation. Here a basal conglomerate containing clasts of iron-formation as much as 0.5 m diameter can be seen. The angular clasts have features indicative of brittle fracturing, implying that the Negaunee was well lithified prior to the time that these clasts were eroded. Well rounded clasts of vein quartz are also common, most likely derived from a locally exposed basement terrane. The lack of other basement rock types in clasts may mean that the surface of exposed basement rocks was deeply weathered so that only vein material persisted in coarse fragments. The exposures seen here are only a few feet above the unconformity and Negaunee Iron-formation was mined from small pits immediately south of the outcrop.

Conglomerate units such as seen here are typically lenticular. They range up to a few hundred feet thick locally but pinch out along strike so that quartzite commonly lies on the Negaunee with little or no conglomerate. The coarse conglomerate lenses may have been alluvial fans along the scarps of faults that were active during deposition. The features seen here suggest a rather long time interval across the unconformity and renewed deposition during reactivation of basement faults. One interpretation is that the Menominee Group was deposited during continental breakup on a rifting margin and that the Baraga Group, beginning with the Goodrich Quartzite, was deposited in a foreland basin at the outset of collision with volcanic terranes now seen in northern Wisconsin.

Stop 5. Chocoday Group and lower part of Menominee Group (Ajibik Quartzite and Siamo Slate)

The series of roadcuts along U.S. Highway 41 exposes much of the stratigraphy of the lower part of the Marquette Range Supergroup. The easternmost cut shows a few tens of feet of green chloritic slate mapped as the upper part of the Enchantment Lake Formation. Here the Enchantment Lake differs significantly from that seen at stop 1 in being much thinner, probably not much thicker than the section exposed here, and it lacks conglomerate beds. The Enchantment Lake grades over a few feet into the overlying vitreous quartzite of the Mesnard Quartzite, essentially similar to that seen at stop 2. The Ajibik Quartzite is exposed in the next set of roadcuts to the west. Although similar in appearance to the Mesnard, the Ajibik in general is somewhat more feldspathic. The geology near here was mapped in detail by Willard Puffett to document the relationship between the two quartzite units. Puffett was able to trace a distinctive granule bed, about 10 inches thick near the base of the Ajibik and show that the Ajibik cuts across the Mesnard at a low angle, demonstrating the angular unconformable nature of the contact. The thinness of the Chocoday Group here and the absence of the Kona Dolomite reflect the westward beveling of the group by the Ajibik. Within a mile west of here the Chocoday Group is absent and the Ajibik rests directly on Archean rocks.

The Ajibik grades upward into the Siamo Slate seen in roadcuts about 1000 feet farther west on the south side of the highway. The Siamo is a lithologic mixture of slate, arkosic quartzite, and graywacke, generally in beds from a few inches to a few feet thick. The rock here has a prominent cleavage that dips southward more steeply than bedding, consistent with the location on the north limb of the Marquette synclinorium. An interesting and controversial feature of this outcrop is lenses of graywacke that lie within

the cleavage and transect bedding. Various authors have interpreted these as clastic dikes or as lithified beds tectonically forced into cleavage planes.

Stop 6. Negaunee Iron-formation (carbonate facies)

This stop, near the old Athens Mine, shows carbonate facies iron-formation typical of much of the lower part of the Negaunee Iron-formation. The iron-formation seen here consists mainly of alternating laminae of sideritic carbonate and chert, but some layers contain as much as 15% minnesotaite, which imparts a greenish color. Some layers contain small amounts of magnetite, but in general the rock is only weakly magnetic. Thin sills of altered metadiabase, less than a foot thick, are also present in the exposure.

This exposure provides striking examples of the effects of surface weathering and oxidation and replacement of sideritic iron-formation. The weathering has taken place in the relatively few decades since the road cut (originally a railroad cut) was excavated. Oxidation has advanced inward from cracks and exposed surfaces, first converting layers rich in carbonate into yellow brown to reddish brown goethitic iron oxide, and eventually changing even chert laminae into iron oxide. These surficial effects are analogous to those that formed the "soft ores" of the region. The major ore bodies in the eastern end of the iron range, including those in the immediate vicinity of this stop, were replacement masses of iron oxides and hydroxides formed by low temperature alteration of carbonate and silicate iron-formation accompanied by dissolution and replacement of chert.

Stop 7. Negaunee Iron-formation (hematite-jasper facies)

Classic exposures of the jaspillitic upper part of the Negaunee Iron-formation are seen on Jasper Knob. These exposures are in the central part of the Marquette synclinorium, just north of the major fold axis of the district. The knob itself is on a west-plunging anticline so that the base of the Goodrich Quartzite wraps around the west end of the knob and is exposed in some of the fenced mined areas near the base of the west slope. The iron-formation here characteristically has alternating thin beds of specular hematite and bright red jasper. Specularite plates are strongly oriented parallel to bedding in the hematitic layers.

Folds having drag folds on their limbs and themselves being drag folds on the limbs of still larger folds are strikingly shown in many exposures. Fold axes are horizontal to gently plunging. Small breccia zones are common and appear to lie roughly along axial planes of folds. In these zones fractured jasper beds are surrounded by crystalline hematite.

Two theories have been advanced for the origin of the jaspillite. One advocates oxidation of siderite-chert iron-formation during the post-Negaunee erosional interval and its recrystallization to specularite-jasper during Penokean deformation and metamorphism. This theory accounts for patches of specularite-jasper within carbonate facies iron-formation near contacts between the two rock types, as, for example, in the Cliffs Shaft mine about ½ mile to the west. The second theory advocates a primary origin for the hematite and jasper in a more oxidizing depositional environment than that responsible for carbonate iron-formation. The even-bedded and thin-bedded nature of the jaspillite on Jasper Knob is very similar to the bedding characteristics of carbonate iron-formation. It contrasts sharply with wavy bedding and oolitic structure common in jaspillite elsewhere in the district. At the Kloman Mine, near Republic (stop 10), a convincing case can be made for a primary depositional origin of jaspillite. Here, at Jasper Knob, an origin by oxidation of carbonate iron-formation is more possible.

Stop 8. Michigamme Formation, lower slate member.

The lower part of the Michigamme Formation consists of black sulfidic slate well represented by the outcrops along the south side of Highway 41. This outcrop is near the axis of the Marquette synclinorium. Subtle beds show mostly low dips and gentle folds with nearly horizontal axes. A steep axial plane cleavage is well developed. Very fine-grained pyrite is abundant in many beds. This black slate facies lies on the Goodrich Quartzite and is overlain by the Greenwood Iron-formation Member, a lean silicate-magnetite iron-formation.

Stop 9. Michigamme Formation, Clarksburg Volcanics Member.

The Clarksburg Volcanics is a local unit resting on the Greenwood Iron-formation Member. The volcanic rocks are restricted to the south limb of the Marquette synclinorium, where they are exposed along a strike length of about 15 miles and range up to about 1 mile thick. The absence of volcanic rocks on the north limb of the synclinorium, only a few kilometers away, shows that deposition in the Marquette trough was very asymmetrical at this time and that the trough was probably much deeper on the south. Lenses of lean iron-formation at numerous stratigraphic horizons throughout the volcanic section indicate that volcanism was mostly or entirely submarine.

The volcanics are almost exclusively mafic and pyroclastic. This outcrop along the north side of the abandoned railroad grade is representative of the unit in which layering is shown distinctly by variations in fragment size, most fragments are angular pieces of highly vesicular mafic rock, and the matrix is rich in carbonate minerals. Fragments of argillite and chert are also present. Rocks here are metamorphosed to garnet grade and original mafic minerals are converted to amphibole and biotite. In spite of the recrystallization, original igneous textures are very well preserved, even at microscopic scales. Low outcrops south of the railroad grade show lean, impure iron-formation typical of lenses that are widespread in the Clarksburg Volcanics. The rocks consist of alternating layers of magnetic biotite argillite and siliceous beds with abundant fine-grained muscovite.

Stop 10. Negaunee Iron-formation at Kloman Mine.

Exposures here are of the uppermost units of the Negaunee Iron-formation. Interbedded on a scale of one to three feet are two contrasting lithologic types of iron-formation, a wavy-bedded, oolitic jaspillite and even-bedded cherty grunerite-magnetite iron-formation. The features seen in this exposure were instrumental in Hal James' formulation in the 1950's of his concepts of sedimentary facies of iron-formation as well as oxygen-buffering by contrasting mineral assemblages during high grade metamorphism. A critical feature very well shown here is a correspondence between bedding characteristics and oxidation state. Relatively reduced rocks, now grunerite-magnetite assemblages, are invariably in thin, even beds, probably reflecting deposition in quiet, poorly oxygenated water. Interbeds of jaspillite invariably show irregular wavy beds and oolites are common, especially in thicker jasper beds. These units are believed to have formed in agitated, more oxygenated water. James used this correspondence of sedimentary features and mineral assemblages to argue that the different lithologies and their oxidation states, although metamorphosed to sillimanite grade here, still reflect differences in primary depositional settings.

Stop 11. Michigamme Formation.

This roadcut shows very highly deformed schist of the Michigamme Formation in the axis of the northwest-plunging Republic trough. The rock here consists of iron-rich metasediments, now consisting of biotite-garnet-amphibole schist. The light-colored bladed amphibole is commonly mistaken for sillimanite, but although this exposure is within the sillimanite metamorphic zone, detailed petrographic examination has failed to find sillimanite in this outcrop. Thicker beds, up to a few inches, of impure quartzite form readily traceable marker beds and reveal very tight folds with amplitudes many times greater than wavelength, and highly attenuated limbs. Fold axes, even in adjacent folds, diverge by as much as 60°. The very tight folding is caused, in large part, by compression of the metasediments between two blocks of Archean gneissic rocks that flank the Republic trough on the northeast and southwest sides.

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Field Trip 2

Archean Ishpeming Greenstone Belt and Gold Mineralization, Michigan

**Leaders: T.J. Bornhorst, D.J. Duskin, R.C. Johnson, R.A.
Mahin, T.O. Quigley, and G.W. Scott**

An Introduction to the Archean Ishpeming Greenstone Belt, Michigan

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Theodore J. Bornhorst, Department of Geological Engineering and Sciences,
Michigan Technological University, Houghton, MI 49931

Introduction

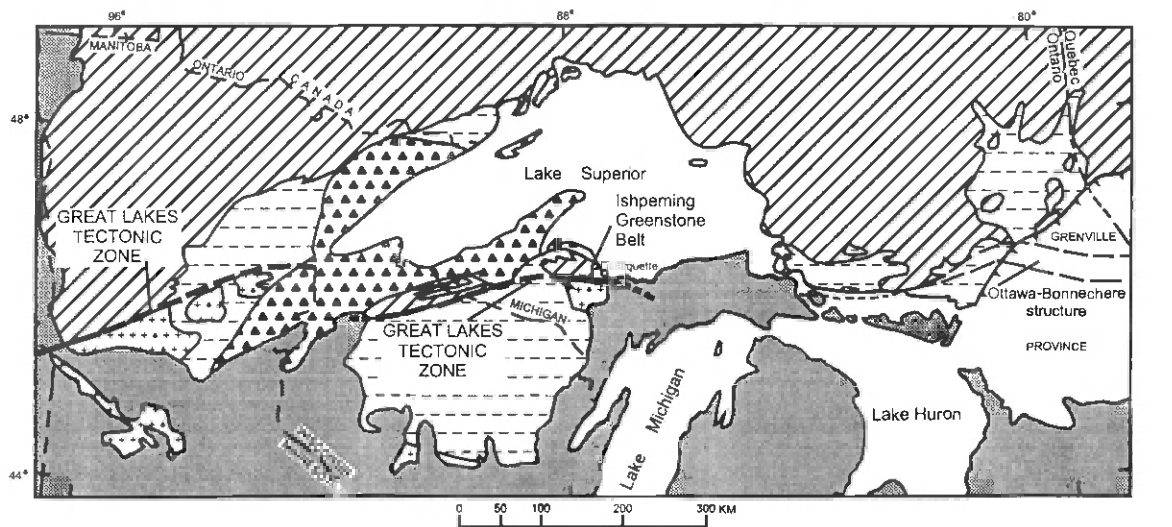
The Ishpeming greenstone belt (IGB) covers an area of about 300 km² and is located in Michigan's Upper Peninsula. It is on the southernmost edge of the Superior province and is part of the Wawa subprovince (Figure 1). The belt is composed of tholeiitic pillowed basalt flows and lesser amounts of intermediate to felsic volcanic rocks and minor clastic and chemical sedimentary rocks. The IGB is about 2,700 Ma (Bornhorst and Johnson, 1998; Hammond, 1978). The IGB is north of the Great Lakes tectonic zone, an Archean continent-continent suture (Sims, 1991). In Michigan, the Archean rocks south of the Great Lake tectonic zone are composed of old Archean gneiss and migmatite intruded by younger Archean granites and is part of the Minnesota River Valley Subprovince (Sims, 1996).

Tholeiitic to calc-alkalic volcanism of the IGB belt resulted from north-directed subduction (Hoffman, 1989; Card, 1990) during Archean time. Successive Archean accretion resulted in southward younging of greenstone belts in the Superior province. The Great Lakes tectonic zone (GLTZ) is a 1,000 km long Archean paleosuture (Sims, 1991), the most significant Archean tectonic boundary within the U.S.A. Sims (1991) has studied a significant shear zone, just south of the IGB, that he has interpreted as the only exposed segment of the GLTZ (Figure 1). The Minnesota segment of the GLTZ is buried. A result of detailed and regional field studies, including structural geology, is the synthesis of the lithostratigraphy of the IGB in close proximity to the Great Lakes tectonic zone.

Structure

Accurate stratigraphic correlation depends on good understanding of deformation history. Recent studies have shown that the rocks of the IGB have been effected by six periods of Archean deformation (Table 1)(Johnson, 1993; Nachatilo and Bauer, 1993). D₁ deformation produced recumbent folds with a flat-lying penetrative, nearly axial-planar cleavage (Johnson and Bornhorst, 1991). D₂ deformation produced large-scale strike-slip shear zones that define the boundaries of lithostratigraphic blocks. D₃ deformation produced upright folds (Figure 2) with a near-vertical axial-planar cleavage that is developed best in felsic volcanic and interflow sedimentary units. D₄ deformation is associated with the intrusion of late trondjemite-granite suite plutons that reorient earlier fabrics. D₅ deformation produced dip-slip motion in shear zones. D₆ deformation produced crenulation cleavage, local kink bands, and strike-slip shear zones. The Archean rocks of the IGB were not significantly deformed during the Early Proterozoic Penokean Orogeny (Nachatilo and Bauer, 1993).

The strata of the southwest block (Figure 2) form a steeply west-plunging synformal anticline. This fold is defined by the orientation of bedding. Fieldwork has identified north-



Explanation

Phanerozoic

 Sedimentary rocks

Precambrian

 Middle Proterozoic volcanic and sedimentary rocks

 Early Proterozoic sedimentary and volcanic rocks

 Archean greenstone-granite complexes

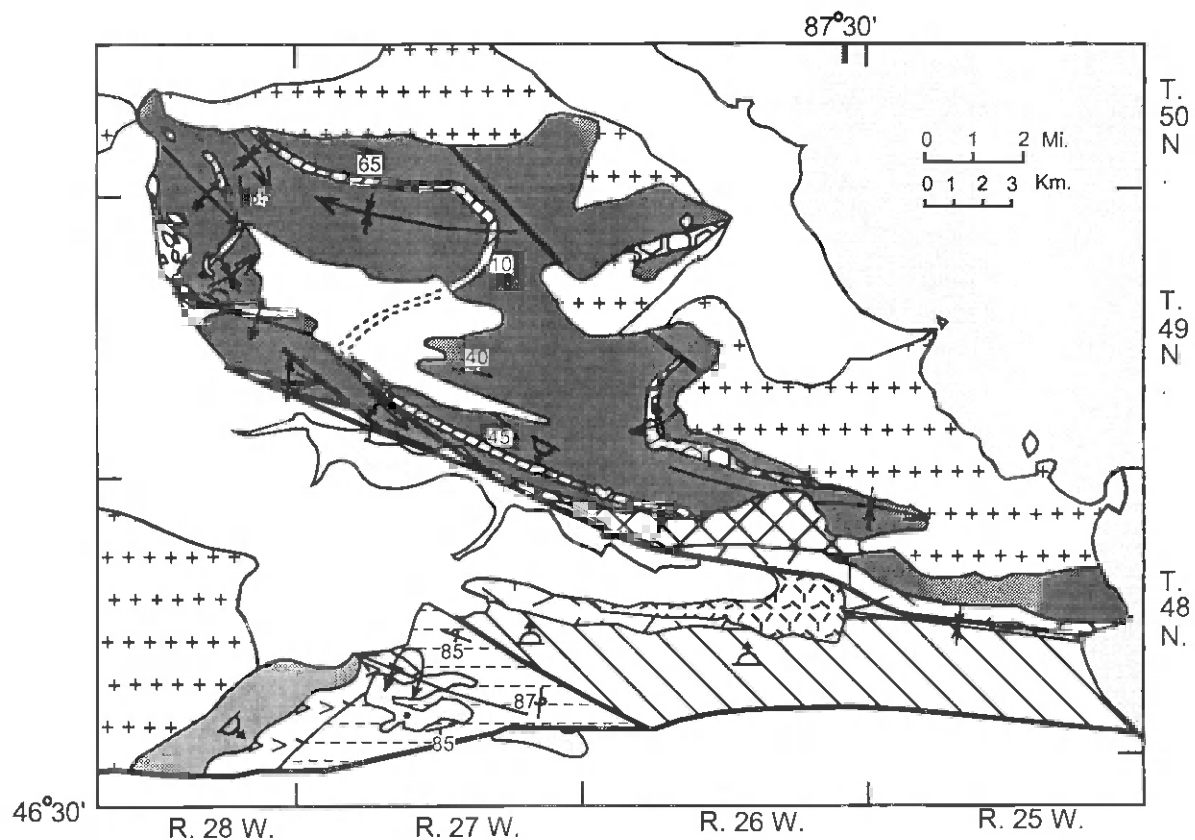
 Archean gneiss and local granitoid rocks

 Grenville front boundary fault

 Fault

 Margins of Great Lakes tectonic zone; short dashed where inferred or covered

Figure 1: Regional geologic setting of the Archean Ishpeming greenstone belt and Archean Great Lakes tectonic zone.



Explanation

Proterozoic

□ Sedimentary rocks

Archean

Intrusive Rocks

▨ Granodiorite

++++ Tonalite

>>> Deer Lake Peridotite

Sedimentary Rocks

▨ Timiskaming-type sedimentary rocks

Volcanic Rocks

Lighthouse Point Basalt

▨ Basalt

▨ Reany Lake pyroclastic unit and
Fire Center mine iron-formation unit

▨ Nash Creek glomerophytic basalt unit

Mona Formation

▨ Upper tuff unit and lapilli-tuff unit

▨ Basalt flow unit

Kitchi Formation

--- Tuff unit and lahar unit

▨ Basalt flow unit

85 T Bedding

87 T Overturned bedding

Facing of pillows

Plunging anticline

Plunging syncline

Plunging overturned anticline

Shear zone

Figure 2: Generalized geologic map of the Ishpeming greenstone belt.

Table 1. Summary of deformation sequence and volcanic/magmatic activity and constraining age dates for the Ishepming greenstone belt.

<u>Event</u>	<u>Characteristic</u>	<u>Volcanic/Magmatic Activity</u>	<u>Age Dates</u>
		Undeformed post-tectonic granite	2585 Ma
D ₆	Kink bands with north-easterly striking kink planes and steeply plunging hinges		
D ₅	Dip slip motion along shear zones.		
D ₄	Folding associated with intrusion of plutons.		
D ₃	Upright folding.	Appinite suite	
D ₂	Strike-slip shearing.	Trondjemite-granite suite	2668.4±2.1/-1.8 Ma
D ₁	Recumbent folding.	Tonalite suite	
		Extrusion of mafic and felsic volcanic rocks.	2705.8±/-1.6 Ma

and northeast-facing beds in tuffaceous units on the northern limb of this D₃ fold. Tuffs of the southwest block have a well-developed axial planar foliation (S₃). Pillow basalts of the southeast block consistently young to the north and have a poorly developed cleavage. Interflow sedimentary rocks dip steeply to the north. Tuffs that overlie the basalts have two well-developed cleavages that define a moderately plunging D₃ synform. The strata of the north block have been re-folded, and sedimentary and felsic volcanoclastic rocks define a broad Z-shaped outcrop pattern (Johnson and Bornhorst, 1991). The low density of sedimentary rocks necessitates relying on pillows in pillow lava for defining younging directions (Figure 2). A well-developed foliation in amphibolite-facies basalt was subsequently refolded by D₃ deformation. D₃ folds are upright, open to tight and have shallow to steeply plunging fold axes.

Stratified Rocks

Bornhorst (1988) subdivided the IGB into three lithostratigraphic blocks that comprise internally consistent stratigraphic units bounded by deformation zones (Figure 3). As a whole, the belt is bounded to the south by Early Proterozoic sedimentary rocks along the Carp River Falls shear zone, a structure that was active from the Archean through the Proterozoic (Puffett, 1974). The southwest block is bounded to the west by Archean granitoid rocks. This contact may be a fault since the boundary is not transitional lit-par-lit as found near the intrusive greenstone-granitoid contact of the north block of the greenstone belt (Johnson and Bornhorst, 1991). The Carp River shear zone separates the southwest block from the southeast block. It is interpreted to be a dextral shear zone with uncertain stratigraphic displacement. The dextral Dead River shear zone separates the two southern blocks from the north block. The north block is bounded to the east, north and west by Archean granitoid rocks that have intrusive relationships with the volcanic rocks (Wilkins and Bornhorst, 1992; Johnson and Bornhorst, 1991).

Southwest Block

The southwest block is composed of mafic flows and intermediate to felsic volcanic and volcanoclastic rocks of the Kitchi Formation which are subdivided into three informal units: basalt flow, tuff, and lahar units (Figure 4 and 5). The basalt flow unit, at the base of the Kitchi Formation is composed of 1,800 meters of dominantly pillowed basalt flows, but includes massive basalt flows as well. The basalts are dominantly magnesian tholeiites composed of hornblende-actinolite-albite-chlorite-clinzoisite with minor amounts of sphene, magnetite, and (or) pyrite. The base of the basalt flow unit is in probable fault contact with Archean granitoid rocks. Several thin beds of chert and dacite to rhyolite tuff are interlayered near the middle of the basalt flow unit. Near the top of the basalt flow unit is a 30-meter-thick glomerophytic flow containing plagioclase phenocrysts up to 2 cm in diameter. The uppermost basalt flows intercalate with intermediate volcanic rocks of the overlying tuff unit. The tuff unit of the Kitchi Formation is composed of 5,000 meters of tuff with lesser amounts of interlayered lahar with the thicker beds of lahar separated into the lahar unit. The tuff unit consists of crystal and lithic tuffs, with minor lapilli-ash and ash tuffs, dominantly calc-alkalic andesite in composition. The rocks are schist composed of quartz-feldspar-sericite-chlorite containing quartz and feldspar phenocrysts. Pillowed basalt flows interfinger with

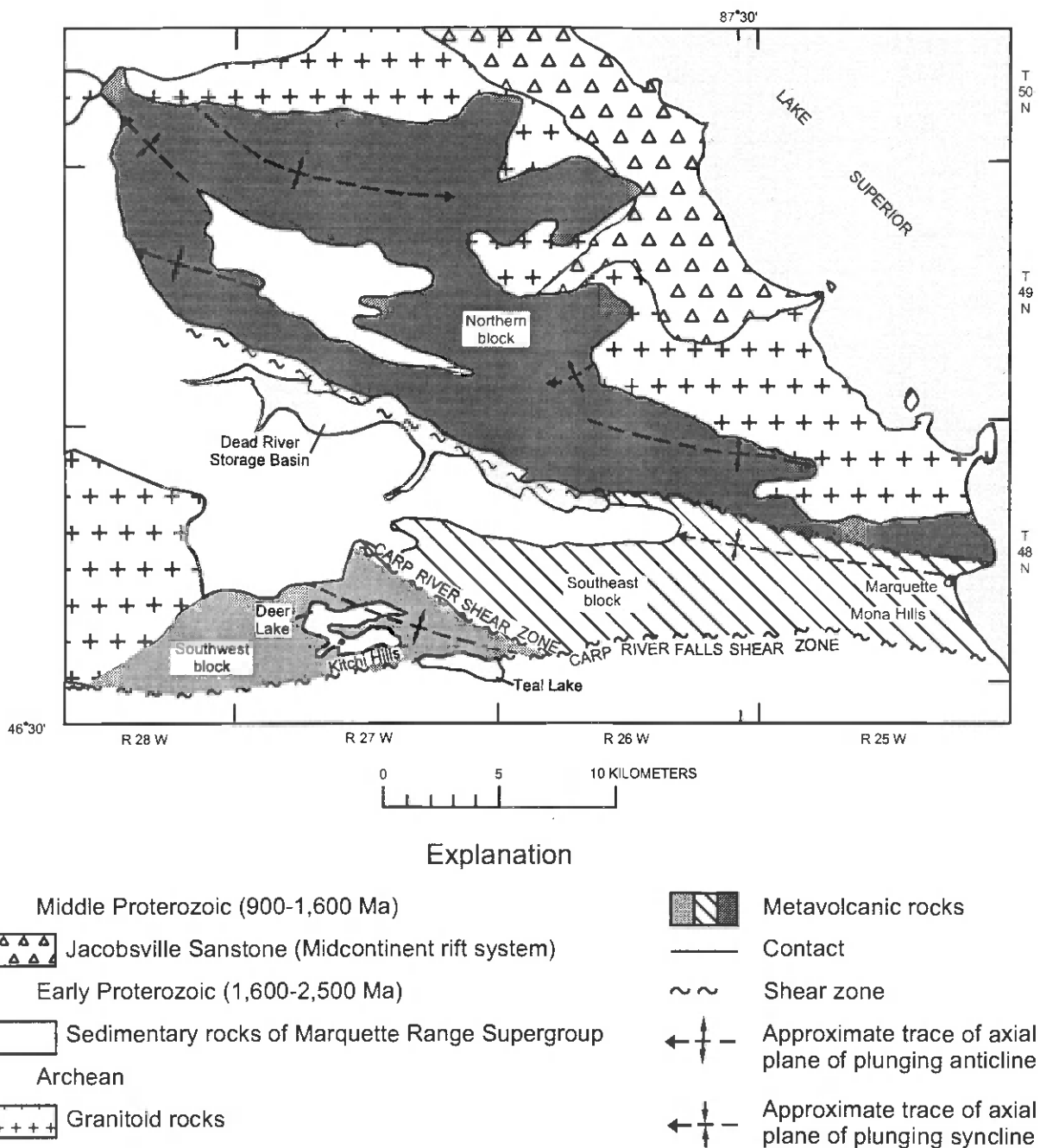
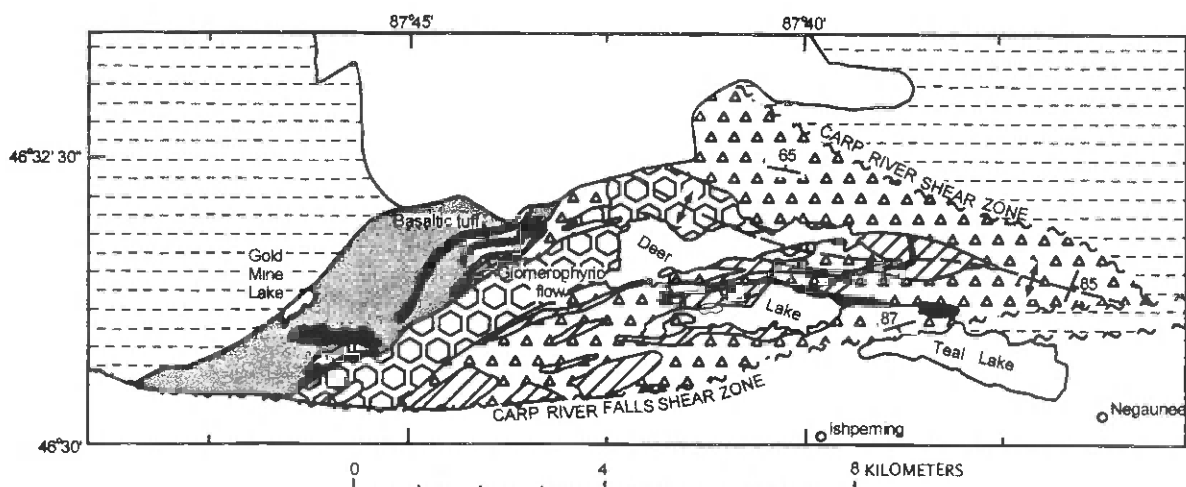


Figure 3: Lithostratigraphic blocks of the Ishpeming greenstone belt.



Explanation

Early Proterozoic	
	Undifferentiated metasedimentary rocks
Archean	
	Undifferentiated rocks
	Metagabbro
	Deer Lake Peridotite
Kitchi Formation	
	Lahar unit
	Tuff unit
	Basalt flow unit
	Contact
	Strike and dip of beds
	Shear zone
	Approximate trace of axial plane of anticline

Note: All rocks are metamorphosed

Figure 4: Generalized geologic map of the southwest block of the Ishpeming greenstone belt.

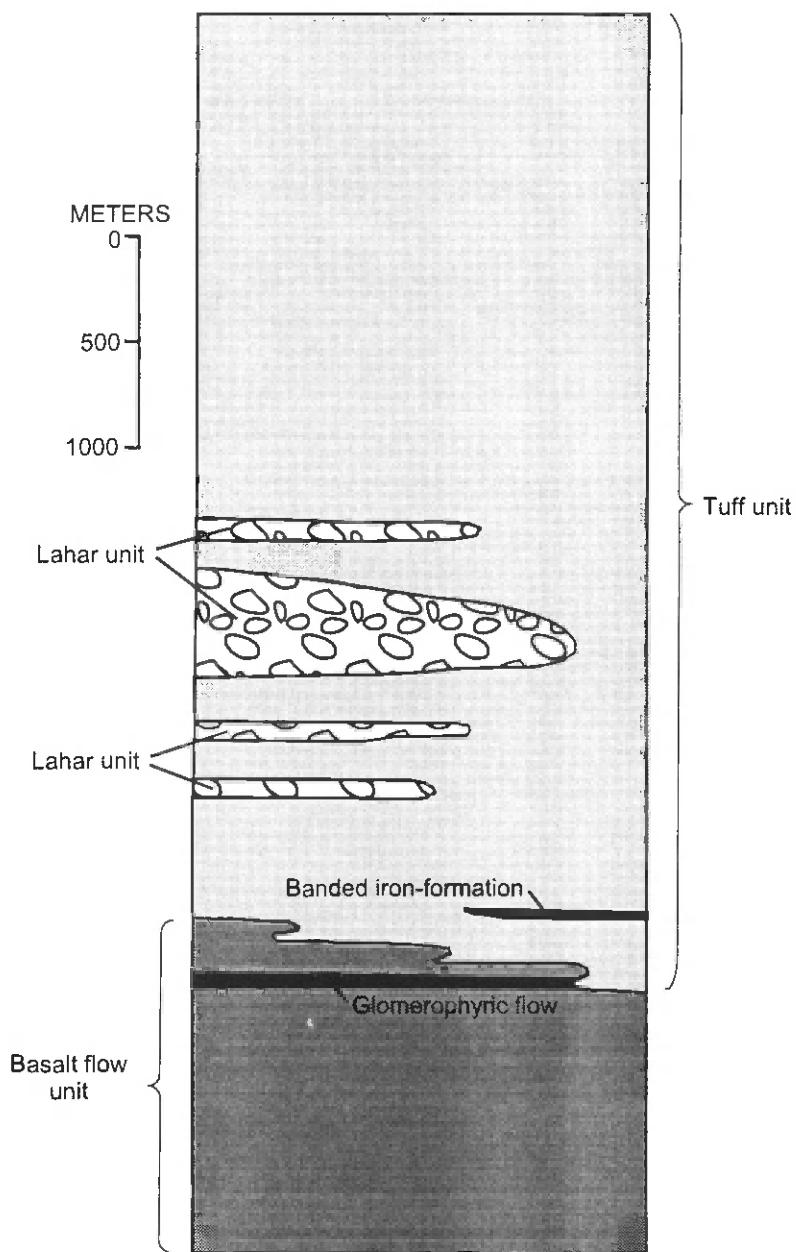


Figure 5: Generalized stratigraphy of the Kitchi Formation within the southwest block of the Ishpeming greenstone belt.

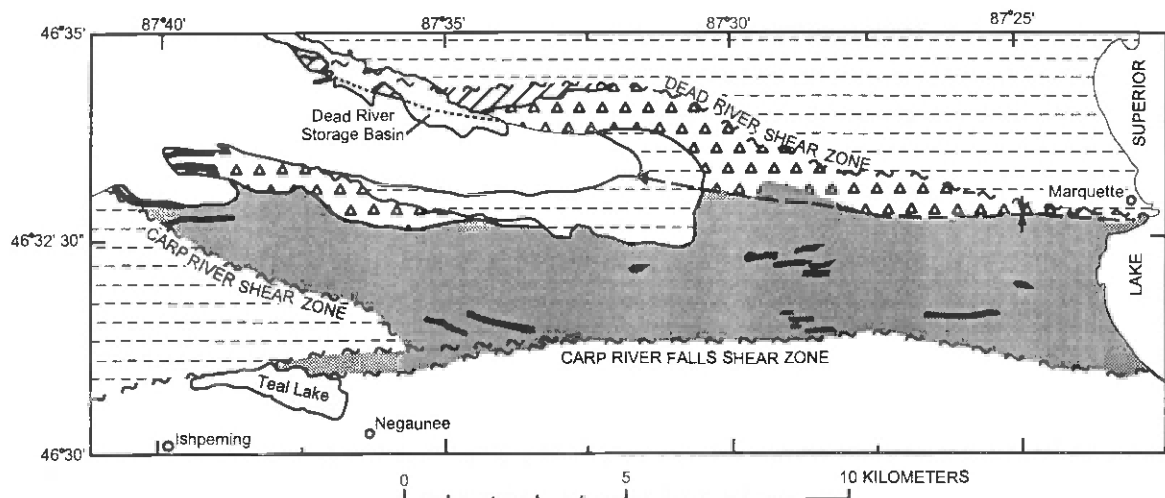
the tuff unit near the top and base of the unit. The lahar unit of the Kitchi Formation is composed of beds and lenses of polymictic volcanic conglomerate containing clasts of thinly laminated, porphyritic, and holocrystalline rocks that are calc-alkalic andesite to dacite in composition. The polymictic volcanic conglomerates are more common near the base of the tuff unit and are interpreted as lahar deposits (Bornhorst and Johnson, 1993).

Southeast Block

The southeast block is composed of basalt flows and felsic volcanic and volcanoclastic rocks of the Mona Formation, which is subdivided into informal units: basalt flow, lapilli-tuff, and upper tuff units (Figure 6). The basalt flow unit, at the base of the Mona Formation, is a 5,500-meter-thick sequence of pillowed with minor massive basalt flows. The basalts are dominantly magnesian tholeiite basalt flows. Within the basalt flow unit are thin interflow chert-magnetite iron formations and schistose quartz-sericite rocks (tuffs). The most notable occurrence of interflow sedimentary rocks in the Mona Formation occurs north of the Pine Hill Quarry (Figure 6). At this location, chert-magnetite and chert-pyrite iron-formation are intercalated with graphite and quartz-sericite schist (tuffs) as interflow units. Diamond drilling along this interval has indicated that these units have a combined thickness of approximately 10 meters. The lapilli-tuff unit overlies the basalt flow unit (Figure 7) and is composed of calc-alkalic rhyolite lapilli in a quartz-sericite-chlorite matrix supporting quartz and, less commonly, feldspar phenocrysts. This unit is interpreted as subaqueous pyroclastic flow and fall deposits (Bornhorst and Johnson, 1993). The lapilli-tuff unit grades laterally and vertically into the upper tuff unit. This unit is composed of quartz-feldspar-sericite-chlorite schist with a bulk calc-alkalic dacite composition. It is interpreted as interbedded tuffs and volcanic derived graywacke (Bornhorst and Johnson, 1993). The combined thickness of these felsic volcanic and volcanoclastic units is 900 meters.

North Block

The north block is composed of the 3,100-meter-thick Lighthouse Point Basalt (Figure 8). The Lighthouse Point Basalt is dominantly pillowed tholeiitic-magnesian basalt flows with minor massive flows. A glomerophyric (Nash Creek) basalt flow occurs near the base (Figure 9). Within the Lighthouse Point Basalt, the Reany Lake pyroclastic unit is composed of interbedded ash to lapilli ash tuffs of calc-alkalic dacite composition. It is in turn overlain by the Fire Center mine iron-formation unit – a thinly bedded chert-magnetite iron-formation with lesser amounts of associated chlorite-magnetite schist and chert-pyrite iron-formation. Over-lying the iron-formation is intercalated chlorite-carbonate-feldspar and quartz-chlorite schist (tuffs). Above and below the iron-formation are isolated lenses and pods of graphite-pyrite schist. This interval of sedimentary rocks is poorly exposed, but has an estimated thickness of approximately 100 meters. The Reany Lake pyroclastic unit also crops out in the vicinity of Hills Lakes where it is composed of lapilli and ash tuffs of calc-alkalic dacite to rhyolite composition. The Lighthouse Point Basalt represents a succession of subaqueous tholeiite basalt flows with intercalated distal to nearly proximal felsic volcanic rocks (Johnson and Bornhorst, 1991).



Explanation

	Undifferentiated metasedimentary rocks		Lapilli-tuff unit
ARCHEAN			Basalt flow unit
	Undifferentiated rocks		Contact--Dashed where concealed
	Metagabbro		Shear zone
Mona Formation			Approximate trace of axial plane of plunging syncline
	Upper tuff unit		

Note: All rocks are metamorphosed

Figure 6: Generalized geologic map of the southeast block of the Ishpeming greenstone belt.

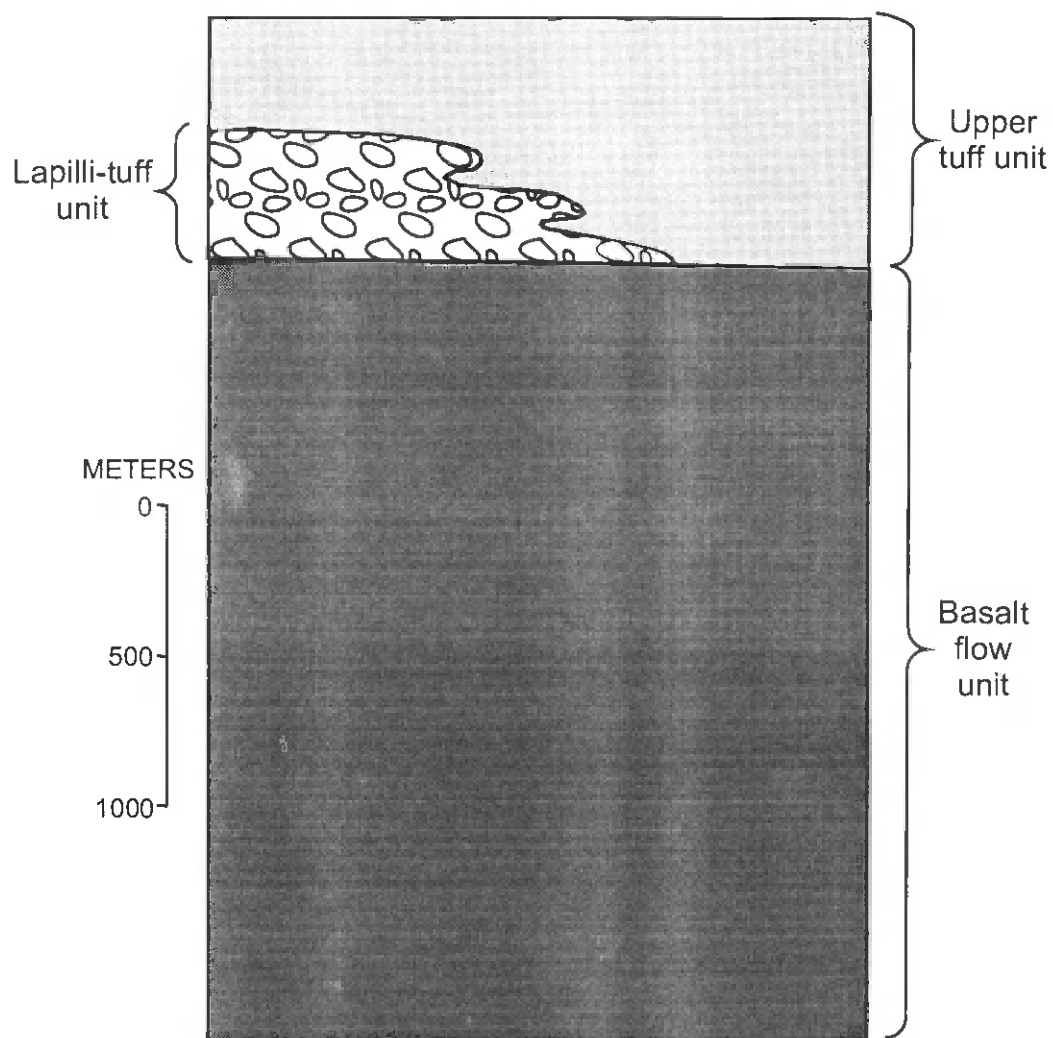
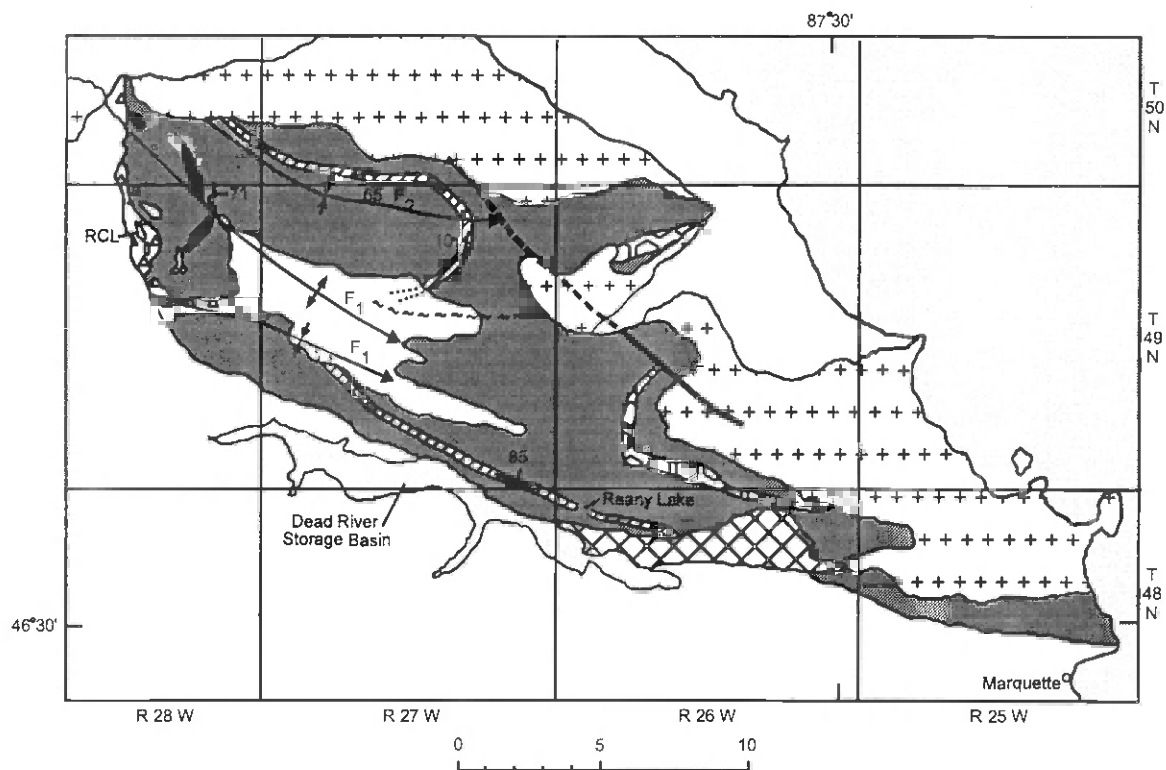


Figure 7: Generalized stratigraphy of the Mona Formation within the southeast block of the Ispeming greenstone belt.



Explanation

	Sedimentary rocks of Middle and Early Proterozoic ages		Fire Center mine iron-formation and Reany Lake pyroclastic units
	Reany Creek Formation		Nash Creek glomerophytic basalt unit
	Granodiorite near Rocking Chair Lakes		Fault—Dashed where inferred
	Gneissic granite to tonalite		Shear zone
	Lighthouse Point Basalt		Strike and dip of overturned bedding
	Hills Lakes pyroclastic unit		Approximate trace of axial plane of plunging anticline
			Approximate trace of axial plane of plunging syncline

Figure 8: Generalized geologic map of the north block of the Ishpeming greenstone belt.

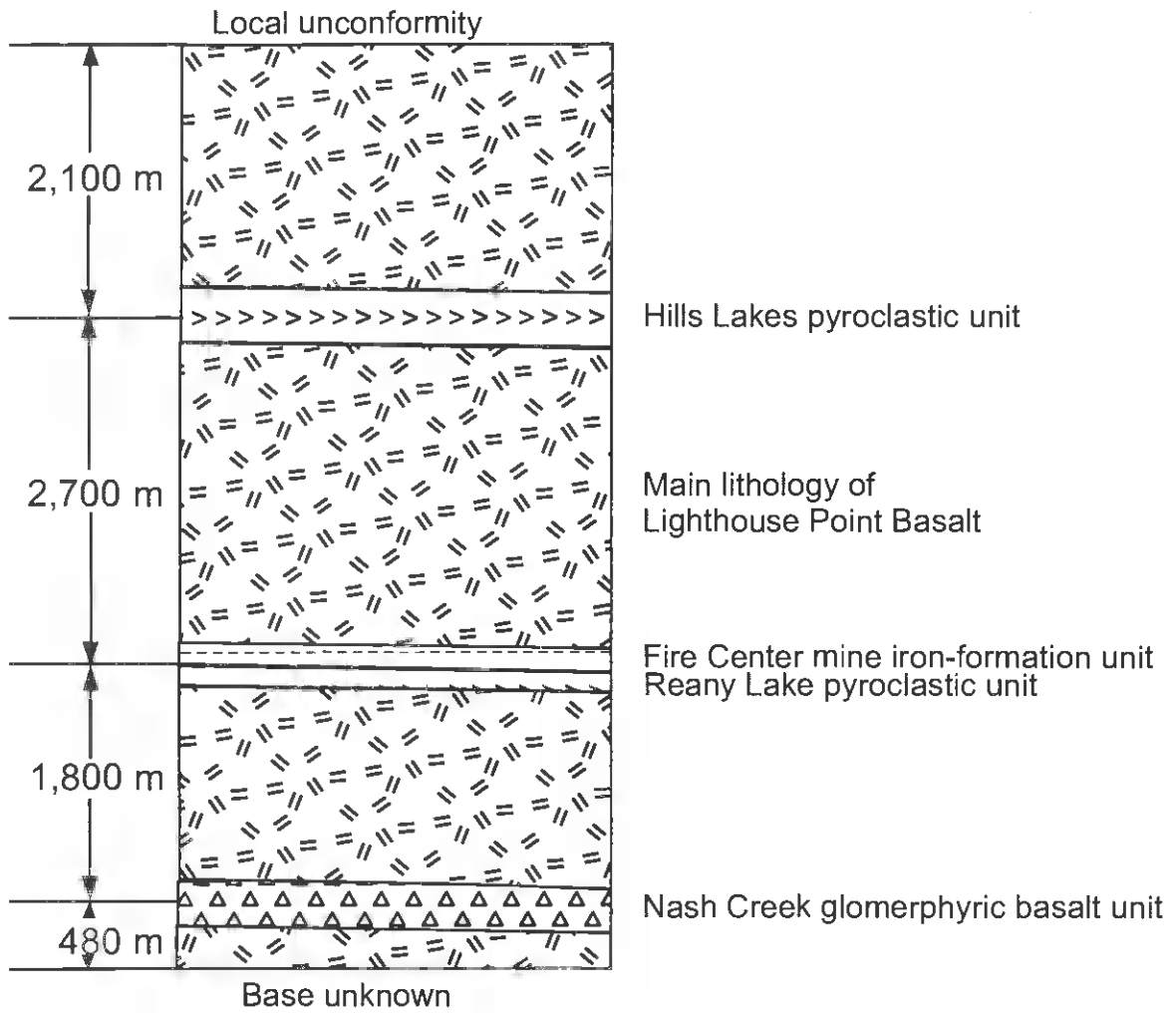


Figure 9: Generalized stratigraphy of the Lighthouse Point Basalt within the north block of the Ishpeming greenstone belt.

Stratigraphic Relationships Among Lithostratigraphic Blocks

Stratigraphic correlations made across major shear zones are tenuous. The folded rocks in the southwest block comprise a steep westward plunging synformal anticline, with tops to bedding on the north limb facing northward (Figure 2). Pillows in the southeast block consistently young to the north, thus strata of the southeast block could be interpreted as younger than and overlying strata of the southwest block. Displacement along the Carp River shear zone may have eliminated some of the stratigraphic section. However, it could also be argued that the stratigraphy of the southwest and southeast blocks may have been juxtaposed by thrusting along the Carp River shear zone making stratigraphic relationships between them indeterminate but evidence for thrusting is lacking.

The stratigraphic units of the north block and the southeast block face each other across the Dead River Basin, but are separated by the Dead River shear zone (Figure 2). The strata of the southeast block consist of pillowed and massive tholeiitic basalt flows overlain by calc-alkalic tuffs and lapilli-tuff. The Lighthouse Point Basalt and the Mona Formation may represent the opposing limbs of a synform. This is much more speculative than the stratigraphic correlation between the southeast and southwest block.

If each block is stratigraphically unique and represents distinct and separate strata, the total stratigraphic thickness is 16,000 meters. If all three blocks are correlatable with one another, the cumulative thickness is 13,000 meters.

Intrusive Rocks

The rocks of the IGB have been intruded by multiple episodes of Archean mafic and felsic magmas. The oldest intrusive rocks are synvolcanic gabbro and peridotite sills. The gabbros are chemically indistinguishable from the surrounding basalt flows and likely represent subvolcanic intrusions (Bornhorst and Johnson, 1993). The Deer Lake Peridotite is intruded between the basalt and tuff units of the Kitchi Formation. Contacts with surrounding volcanic rocks are conformable, but lack of quench textures (spinifex), pillow structures, or other features typical of ultramafic flows lead to the interpretation of the peridotite body as a sill complex (Bornhorst and Johnson, 1993; Brozdowski, 1990; Bornhorst et al., 1986). The peridotite is lherzolite to harzburgite in composition (Rossell, 1983) and similar to ultramafic flows and sills from other Archean greenstone belts.

The oldest felsic intrusive bodies are foliated diorite to granite gneiss batholiths that intrude the margins of the greenstone belt. These intrusions post-date mafic volcanism in the greenstone belt and were deformed along with volcanic rocks during the earliest stage of deformation. Archean granodiorite to syenite stocks and quartz-feldspar porphyry dikes cut the greenstone belt and are interpreted to be synchronous with D₂ through D₄ deformation (Wilkin and Bornhorst, 1992).

Discussion

Structural studies in the IGB have led to a more accurate picture of stratigraphic thickness within lithostratigraphic blocks and possible correlations between blocks. Geological studies prior to 1988 (Bornhorst) did not recognize the stratigraphic significance of lithostratigraphic blocks. The recognition of the synformal anticline in the southwest block allows the true thickness of the volcanic strata of the Kitchi Formation to be estimated at 6,800 meters, a four fold increase over the +1,500 meter thickness estimated by Morgan and DeCristoforo (1980). The recognition of polyphase deformation in the Lighthouse Point Basalt of the north block lead to a thickness estimate of 3,000 meters, compared to an earlier estimate of 4,500 meters (Morgan and DeCristoforo, 1980).

The stratigraphy of the IGB can be compared to that of the Abitibi greenstone belt. In particular, the volcanic stratigraphy can be compared to the Tisdale Group, which is composed of komatiites and basaltic komatiites at the base overlain by tholeiitic basalts, subsequently overlain by calc-alkalic volcanoclastic rocks (Pyke, 1982). The Tisdale Group has a total thickness of from 950 to 4,000 meters. The IGB has a similar volcanic stratigraphy: tholeiitic basalt (the basalt flow units of the Kitchi and Mona Formations, and the Lighthouse Point Basalt) at the base, succeeded by calc-alkalic volcanoclastic rocks (the tuff unit of the Kitchi and the upper tuff unit of the Mona Formations, and the Reany Lake pyroclastic unit of the Lighthouse Point Basalt). The stratigraphy is even more comparable if the Deer Lake Peridotite represents subvolcanic sills analogous with komatiitic volcanism. Thus, in terms of lithology and thickness the stratigraphy of the IGB is directly comparable to the Abitibi greenstone belt. The IGB represents an Archean volcanic arc assemblage as characterized by Thurston and Chievers (1990).

The environment of deposition is important in identifying potential ore deposits within the IGB. Significant occurrences of volcanogenic massive sulfide deposits are not known in the IGB. Chalcopyrite and sphalerite associated with chert in the Reany Lake pyroclastic unit of the Lighthouse Point Basalt was interpreted by Johnson and Bornhorst (1991) as a massive sulfide deposit incorporated in the pyroclastic flow. Typically, volcanogenic massive sulfides are hosted in greenstone belts that have a greater than average volume of intermediate volcanic, felsic volcanic and sedimentary rocks (Franklin, 1990). The IGB is favorable for VMS deposits because of its considerable stratigraphic thickness. The Ropes gold mine, which was in production in the 1890's, and more recently from 1985 to 1989, is controlled by a shear zone (Bornhorst et al., 1986; Brozdowski, 1990).

Card (1990) suggested that the Superior province grew by Archean accretion, and that Archean volcanism was the result of north directed subduction. A similar sequence of events could explain the Archean geology of the IGB. The mafic to felsic volcanism could have been the result of northward directed subduction. Extra-belt tonalite batholiths, intra-belt granodiorite stocks, and appinite stocks intrude the greenstone belt. The transition from subduction to collision is preserved by the volcanic rocks (subduction related arc) and by intrusive rocks as described by Wilkin and Bornhorst (1992) (transition from subduction to collision).

The volcanic strata of the IGB can be placed in an analogous modern environment. As a result of north directed subduction thick accumulations of pillowed tholeiitic basalt flows (basalt flow units of the Kitchi and Mona Formations and the Lighthouse Point Basalt) were erupted from shield volcanoes. Subsequently, dome complexes developed on the mafic shield volcanoes. Subaqueous pyroclastic and lahar flows (tuff and lahar units of the Kitchi Formation, upper tuff and lapilli-tuff units of the Mona Formation, and pyroclastic units of the Lighthouse Point Basalt) erupted from the dome complexes. The rocks of the IGB represent coalescing volcanoes in an arc complex. Continent-continent collision caused the cessation of volcanism and complex post-deposition deformation.

Summary

The Ishpeming greenstone belt consists of subaqueous tholeiitic basalt to calc-alkalic rhyolite, 10-15 km in total thickness. U-Pb zircon data establish the age of volcanism at 2705.8 ± 1.6 Ma (Bornhorst and Johnson, 1998). The volcanic rocks were enveloped by tonalite suite plutons just before and during the beginning of recumbent folding (Table 1). Strike-slip shear zones and the deposition of clastic sediments into pull-apart basins followed recumbent folding. The belt rocks were then upright folded. A trondhjemite to granite suite intruded the belt and folded earlier fabrics. The timing of deformation is constrained with U-Pb zircon data yielding an age of 2668.4 ± 2.1 Ma for an intrusion in this suite (Bornhorst and Johnson, 1998). Intrusions of hornblende to syenite (appinite suite) and continued movement along shear zones represent the end of deformation. An undeformed post-tectonic granite intrusion has an age of 2585 (Sims, 1991).

These events are readily interpreted in a modern plate tectonic context. North-directed subduction produced a volcanic arc. Subduction-related tonalite intruded the arc just prior to collision of a small continent from the south (southern complex) along the 1000 km long Great Lakes tectonic zone (suture). Collision occurred over an extended period of time with multiple deformation and magmatic events. The appinite suite is characteristic of modern collision-related magmatism. Continuing studies of the IGB and vicinity will help to unravel the tectonic evolution of the southern edge of the Superior Province.

Acknowledgments

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INTRODUCTION TO THE ROPES GOLD DEPOSIT IN THE ISHPEMING GREENSTONE BELT, MICHIGAN

ABSTRACTED WITH PERMISSION FROM GEOLOGY OF THE ROPES GOLD
DEPOSIT BY R.A. BROZDOWSKI (1988)

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Introduction

The southwest part of the greenstone belt (Figure 1) consists of, from west to east: pillowed and massive basalt, hypabyssal gabbro, dacite tuff and subordinate tuff breccia, serpentinitic, fine-grained peridotite of the Deer Lake Peridotite. Volcanic rocks strike northeast, with a major bend to the east northeast at the Bjork-Lundeen prospect, 1.5 km west of the Ropes deposit. Rocks face consistently to the southeast, based on pillows and graded bedding

The Ropes deposit is southeast of a transition from dominantly basalt to the northwest to dominantly dacite tuff to the southeast (Figure 2). Meter-thick banded iron formation and several meter thick greywacke are within the dacite up section from the interlayered basalt and dacite. Sericite progressively overprints and finally totally pseudomorphs feldspar phenocrysts in dacite tuff as the Ropes gold deposit is approached from the west. The deposit is in quartz-sericite-chlorite rock which is interpreted as quartz-sericite altered dacite tuff.

Major Rock Types within the Ropes Deposit

The four major rock types in or immediately bounding the Ropes deposit are (Figures 3 and 4): 1.) fine grained quartz-sericite-chlorite rock which encloses ore, strikes 070° overall, but 080° where it hosts the Ropes deposit, and dips steeply south or vertical. This rock type is bounded north and south by 2.) fine grained carbonate-quartz-chlorite rock which is massive to compositionally layered on a scale of several millimeters. It and the quartz-sericite-chlorite rock are locally complexly interlayered, particularly in the west part of the deposit, and have generally sharp contacts. Carbonate-quartz-chlorite rock is flanked successively, on both the north and south sides by, 3.) fine grained, massive to moderately foliated, carbonate-talc rock, and 4.) fine grained, serpentinitic peridotite which commonly has pseudomorph texture after original olivine and lesser pyroxene. This is variably carbonate-bearing near its contacts with carbonate-talc rock. Contacts between carbonate-quartz-chlorite rock and carbonate-talc rock and between the carbonate-talc rock and the serpentinitic peridotite are generally gradational over one to several meters.

Quartz-Sericite-Chlorite Rock

The main host for gold is light green, massive to slightly foliated, fine grained, quartz-sericite-chlorite rock. This rock is a 080°-striking layer 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

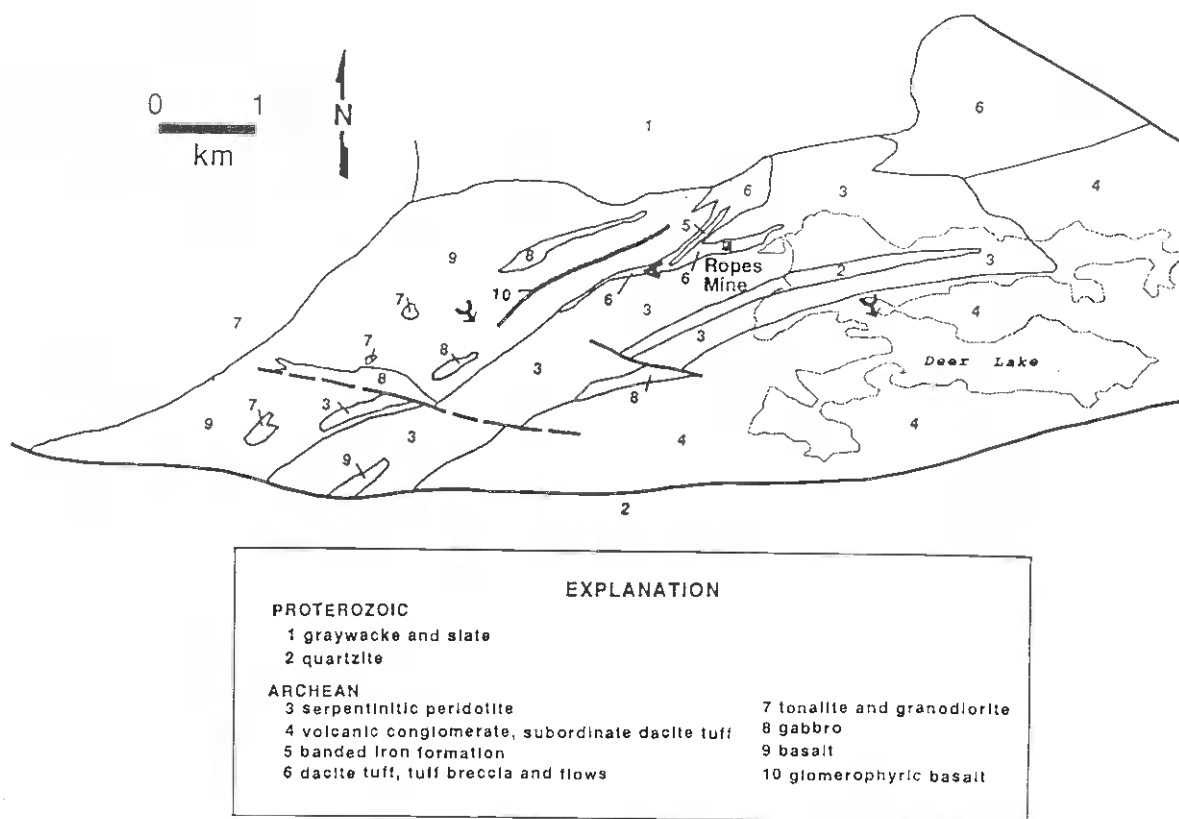
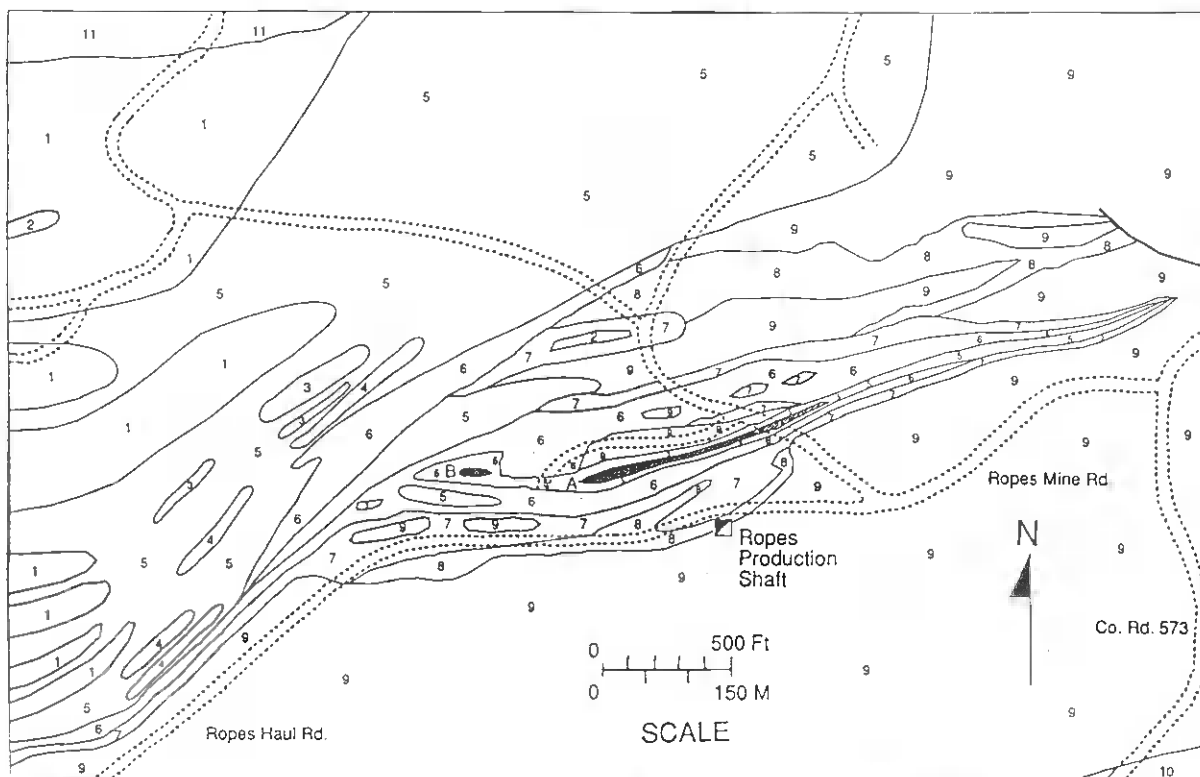


Figure 1: Geologic setting of the Ropes mine in the southwest block of the Ishpeming greenstone belt.



EXPLANATION

PROTEROZOIC	11	GRAYWACKE
	10	QUARTZITE
ARCHEAN	9	SERPENTINITIC PERIDOTITE
	8	CARBONATE RICH, SERPENTINITIC PERIDOTITE
	7	CARBONATE - TALC ROCK
	6	COMPOSITIONALLY LAYERED TO MASSIVE CARBONATE - QUARTZ - CHLORITE ROCK
	5	DACITE TUFF, TUFF BRECCIA, AND FLOWS; (ALTERED TO QUARTZ - SERICITE - CHLORITE ROCK IN ROPES DEPOSIT)
	4	BANDED QUARTZ - MAGNETITE IRON FORMATION
	3	GRAYWACKE AND SILTSTONE
	2	FINE GRAINED GABBRO
	1	BASALT (INCLUDES PILLOWED AND GLOMEROPHYRIC VARIETIES)
		 UPDIP PROJECTION TO SURFACE OF OREBODIES A = main ore zone B = northwest ore zone

Figure 2: Surface geologic map of the Ropes mine and vicinity.

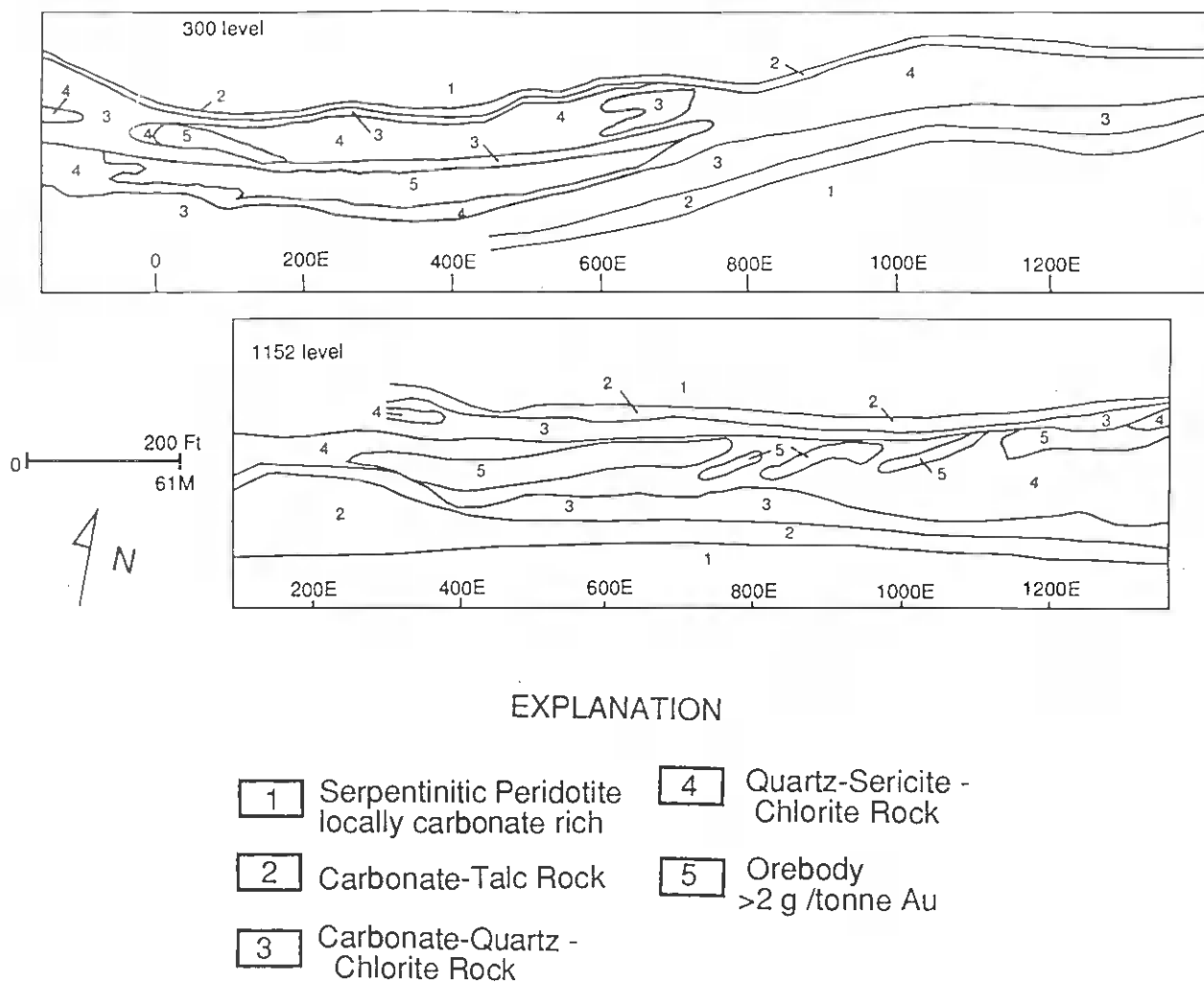


Figure 3: Geologic plan map of the 300 and 1152 levels of the Ropes mine.

ROPES MINE

600 E Cross-Section

Looking S80°W

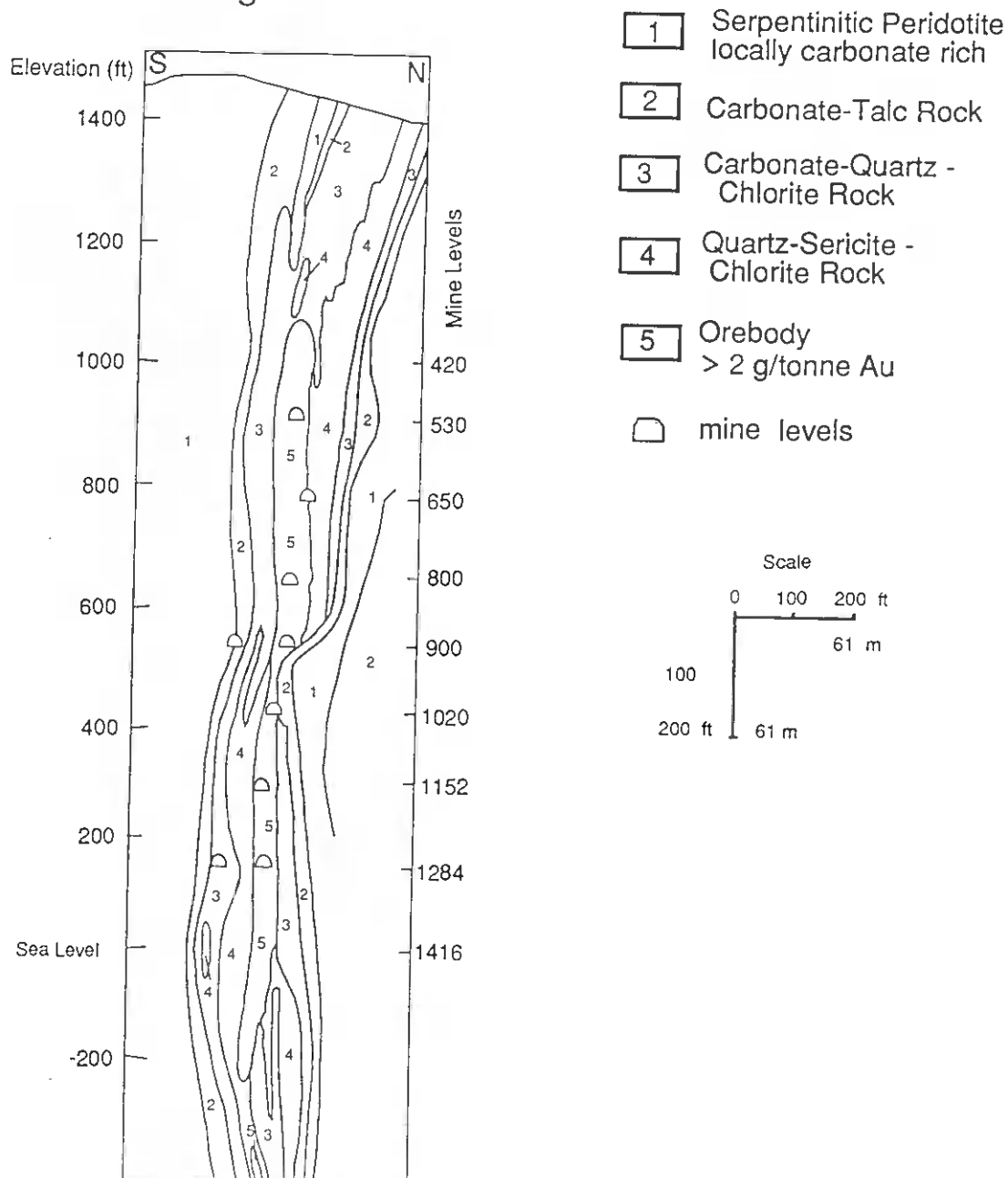


Figure 4: Geologic cross section of the Ropes mine looking S80°W along the 600E section.

complexly interlayered with carbonate-quartz-chlorite rock, especially west of the Ropes main ore zone and in the mine. Randomly oriented to moderately aligned, 1 to 2 mm, angular, rectangular mats of felted sericite up to 2 mm in length, comprised of individual sericite grains less than 10 microns in size, and minor quartz, are enveloped in this matrix and have an external habit identical to plagioclase phenocryst. In dacite tuff immediately west of the deposit there are plagioclase phenocrysts. The rectangular mats are interpreted as pseudomorphs after the plagioclase phenocrysts. The rock is layered locally with 5 mm thick, lens-like, sericite-rich and alternating more chlorite-rich laminae.

Sericite in relict feldspar and lithic clasts in the quartz-sericite-chlorite rock decreases gradationally westward from the Ropes main ore zone over a distance of several hundred meters into a large body of dacite tuff that has moderately aligned twinned plagioclase phenocrysts with only very minor sericite internal to the phenocrysts, bipyramidal quartz, and volcanic rock fragments in an aphanitic quartz-sericite feldspar-chlorite matrix. The dacite tuff outside of the Ropes deposit, proper, has local lapilli-sized fragments as well as tuff breccia layers.

Gold abundance is generally greatest where very fine to aphanitic pyrite is 5 to 8% of the rock, quartz and sericite are most abundant, and chlorite is least abundant. However, this generality does not apply to the chloritic, pyritic, eastern most rim of the Ropes main ore zone. Anastomosing quartz veinlets less than 1 mm thick make up several percent of the rock. Rock outside of the ore zones contains less than 2% very fine pyrite.

The overall 070° striking trend of quartz-sericite-chlorite rock which hosts the Ropes main and northwest ore zones interfingers with carbonate-quartz chlorite rock west of the deposit, and does not continue west of the northwest ore zone (Figure 2). East of the deposit, the trend of quartz-sericite-chlorite rock does not continue at surface beyond 300 m east of the Ropes main ore zone. A zone of carbonate-talc rock within the serpentinitic peridotite marks the east-northeast projection of the trend.

Carbonate-Quartz-Chlorite Rock

Carbonate-quartz-chlorite rock envelopes the quartz-sericite-chlorite rock and is complexly interlayered with it, particularly toward the west end of the Ropes deposit. Carbonate-quartz-chlorite rock is restricted largely to the deposit although layers up to 2 m thick occur up to 400 m west of the Ropes main ore zone. The thickest layers of carbonate-talc rock are immediately north and south of the deposit; however, thin layers of talc-rich rock are at numerous localities at the contacts of, and also within serpentinitic peridotite along the northwest contact of the peridotite up to 500 m away from the deposit.

Carbonate-quartz-chlorite rock contains abundant ferroan dolomite, and lesser quartz and chlorite. Minor sericite is in some parts and variable amounts of talc in others, but these two minerals are generally mutually exclusive. Contacts with quartz-sericite-chlorite rock are sharp in a direction across the strike of the rock type, but are locally gradational along strike. Barren milky quartz veins up to 10 cm thick occur locally and are conformable to the contact. 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 quartz-sericite-chlorite rock. Carbonate-quartz-chlorite rock has up to 150 ppb Au, and quartz rich parts of the carbonate-

quartz-chlorite rock only very locally contain several percent pyrite and up to 1 ppm Au. Locally the carbonate-quartz-chlorite rock is brecciated, with angular fragments of carbonate veined carbonate-quartz-chlorite rock in a chlorite rich matrix particularly at the south side of the deposit.

Carbonate-quartz-chlorite rock is generally compositionally layered on a scale of several millimeters, but locally is massive. Layering is defined by fine to medium grained white carbonate lenses, 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 are several percent of the rock. Carbonate-quartz-chlorite rock is not only within the deposit but also in a zone up to 60 m thick on its north side, where it contains thin layers of the other three main rock types. Carbonate-quartz-chlorite rock is in local lenses along the northeast striking contact of the Deer Lake Peridotite, southwest and northwest of the Ropes deposit. The carbonate-quartz-chlorite rock is interpreted as an alteration product of a serpentinitic peridotite protolith.

Serpentinitic Peridotite and Carbonate-Talc Rock

The interlayered quartz-sericite-chlorite rock and carbonate-quartz-chlorite rocks are bounded on north and south by elongate masses of serpentinitic peridotite. There are also several smaller serpentinitic peridotite bodies enclosed within the carbonate-quartz-chlorite rock on the north side of the Ropes deposit. The largest of these bodies is the north wall of the Ropes deposit. The rock is dark gray to green, mostly fine grained, with major serpentine, subordinate talc and carbonate, minor chlorite, and accessory chromite and magnetite. The serpentine is a mixture of felted chrysotile and oriented plates of antigorite. Commonly it has a relict texture of 1 to 3 mm serpentine pseudomorphs after major olivine and subordinate pyroxene. The pseudomorphs are surrounded by rims of talc, carbonate minerals and accessory fine-grained magnetite and chromite. Locally the rock is dark green, felted textured serpentine which lacks a pseudomorphic texture. The serpentinitic peridotite is increasingly carbonate-rich toward its borders, although the relict texture is commonly continuously preserved. Fibrous chrysotile veinlets in the serpentinite are locally pseudomorphed by carbonate. Au abundance is typically less than 30 ppb, even in close proximity to the deposit.

Massive to well foliated, gray to dark green, very fine grained carbonate-talc rock occurs around the margins of serpentinitic peridotite. Chlorite, serpentine, magnetite and pyrite are minor phases. The carbonate-talc rock has gradational contacts over one to several meters with serpentinitic peridotite and with talc-rich parts of the carbonate-quartz-chlorite rock. Talc and carbonate contents are generally subequal. The carbonate mineral in the carbonate-talc rock is dominantly ferroan dolomite with minor magnesite. Au abundance is from less than 30 ppb to approximately 100 ppb locally in the carbonate-talc rock.

The Gold Ore

The Ropes deposit is 2.8 million tonnes with 3.24 g/ton Au, including production and all categories of reserves. There are two main types of ore: 1.) Ninety five percent of the ore is gold with dispersed pyrite in quartz-sericite-chlorite rock. This ore has several subtypes with varying proportions of quartz, sericite, chlorite, and pyrite. 2.) Five percent of the ore is

auriferous quartz veins with saccharoidal texture and tetrahedrite, pyrite, galena, and chalcopyrite. It is generally at or near the south side of the deposit.

Gold With Dispersed Pyrite in Quartz-Sericite-Chlorite Rock

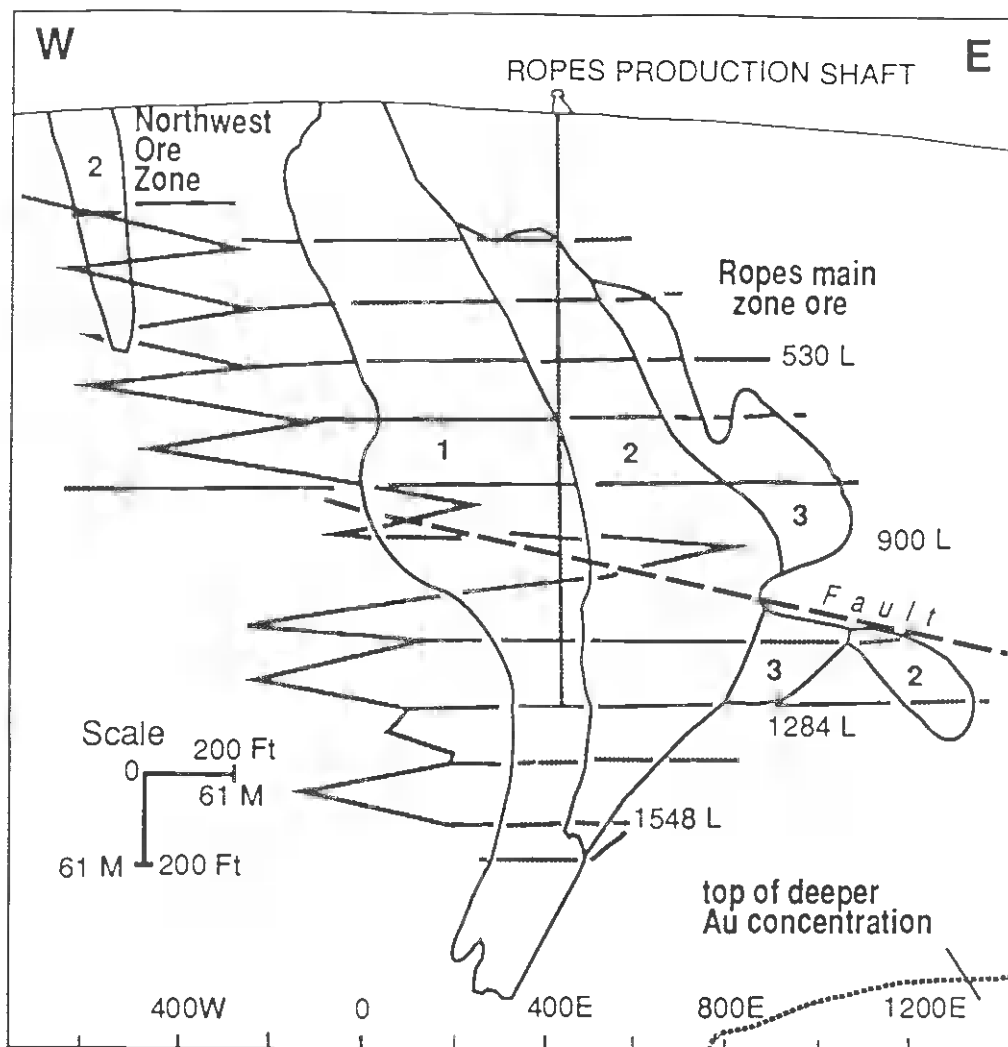
The Ropes main ore zone is steeply dipping, 335 m in maximum strike length, 12 m in average thickness, and 600 m in known down dip extent (Figures 4). It is within the quartz-sericite-chlorite rock, and gold is associated with dispersed pyrite with only minor quartz veins.

The Ropes main ore zone can be divided longitudinally into three ore subtypes (Figure 5). These subtypes are, from west to east, in long section. Subtype 1 is light gray to pale green, siliceous quartz-sericite rock, containing minor lenses of light gray cherty quartz rock with pyrite, tetrahedrite, chalcopyrite and galena. Pyrite abundance does not correlate with gold grade. Subtype 1 has an interdigitating contact with barren quartz-sericite-chlorite and carbonate-quartz-chlorite rock to the west, and a gradational contact to the east with subtype 2. The average gold concentration is 6.8 g/ton. Subtype 2 is light green quartz-sericite-chlorite-pyrite rock with a positive correlation between fine-grained pyrite content and Au abundance. Subtype 2 is the thickest part of the ore zone and, therefore, the most volumetrically important. It has a relatively sharp contact to the east with subtype 3. The average Au concentration ranges from 2.6 g/ton, rarely up to 6.2 g/ton. Subtype 3 is dark green quartz-chlorite-pyrite rock with a consistently large fine-grained pyrite content. It has a sharp contact with barren quartz-sericite-chlorite rock to the east. The average Au concentration is 10.3 g/ton.

Zones of greater than 4 g/ton Au abundance, defined by assay data, are contained centrally within the Ropes main ore zone. The middle parts of these greater than 4 g/ton Au zones strike across the 080° trend of the orebody in an echelon fashion at approximately 055°, whereas their extremities have a nearly 070° strike, thus forming a low angle sigmoidal pattern across the ore zone. This pattern is most pronounced at and below the 1152 level toward the east end of the Ropes main ore zone (Figure 6).

Above the 650 level, ore is separated from carbonate-quartz-chlorite rock on the north by slightly auriferous quartz-sericite-chlorite rock, but below the 650 level the east end of the ore is in contact with carbonate-quartz-chlorite rock (Figure 3). The north side of the ore strikes 070° and dips very steeply north whereas the contact between quartz-sericite-chlorite rock and the carbonate-quartz-chlorite rock strikes 080° within the deposit and dips steeply south. Therefore, at depth, the ore abuts the carbonate-quartz-chlorite rock contact on the north, with the east limit of the Ropes main ore zone plunging to the west at deeper levels along the line defined by the intersection of the planes of the orebody and the carbonate-quartz-chlorite rock contact on the north. Below the 1284 level, the 25 to 40 m thick quartz-sericite-chlorite rock thins markedly to the east and interfingers along strike to the east with carbonate-quartz-chlorite rock. The thickest part of the quartz-sericite-chlorite rock plunges approximately 45° east and is coincident with the bend in strike of the trend of quartz-sericite-chlorite rock from 080° within the deposit back to 070° east of the main ore zone.

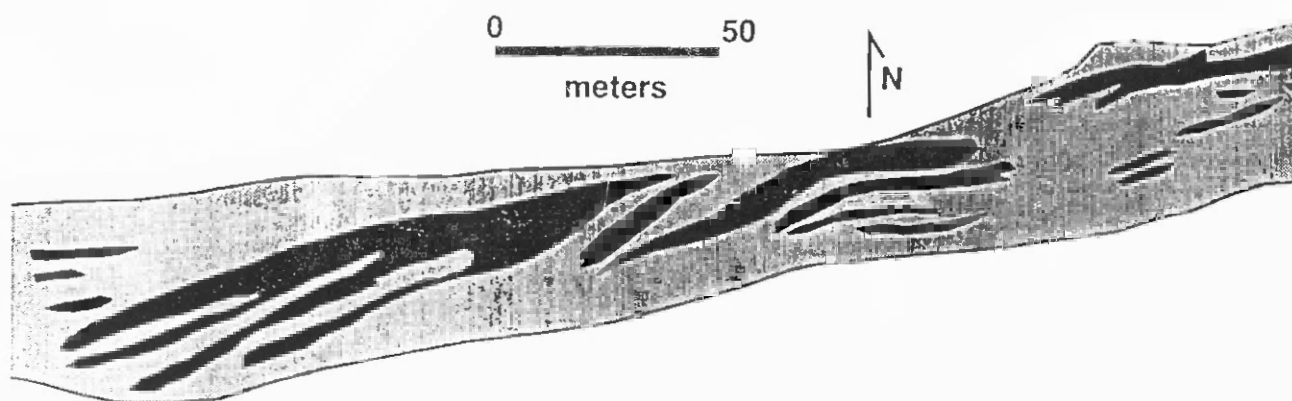
There are several other gold bearing bodies near the main ore zone (Figure 5). The northwest ore zone is a small ore zone of 101,000 tons with 4.6 g/ton Au, 170 m northwest of the Ropes main ore zone, and is dominantly ore subtype 2. Auriferous, pyritic quartz-



Vertical long section of the Ropes deposit in the N80°E plane, with gold ore subtypes:

- | | |
|---|--|
| 1 | QUARTZ - SERICITE ROCK,
WITH GRAY QUARTZ LENSES |
| 2 | QUARTZ - SERICITE - CHLORITE ROCK,
GOOD Au : PYRITE CORRELATION |
| 3 | QUARTZ - CHLORITE - PYRITE ROCK |

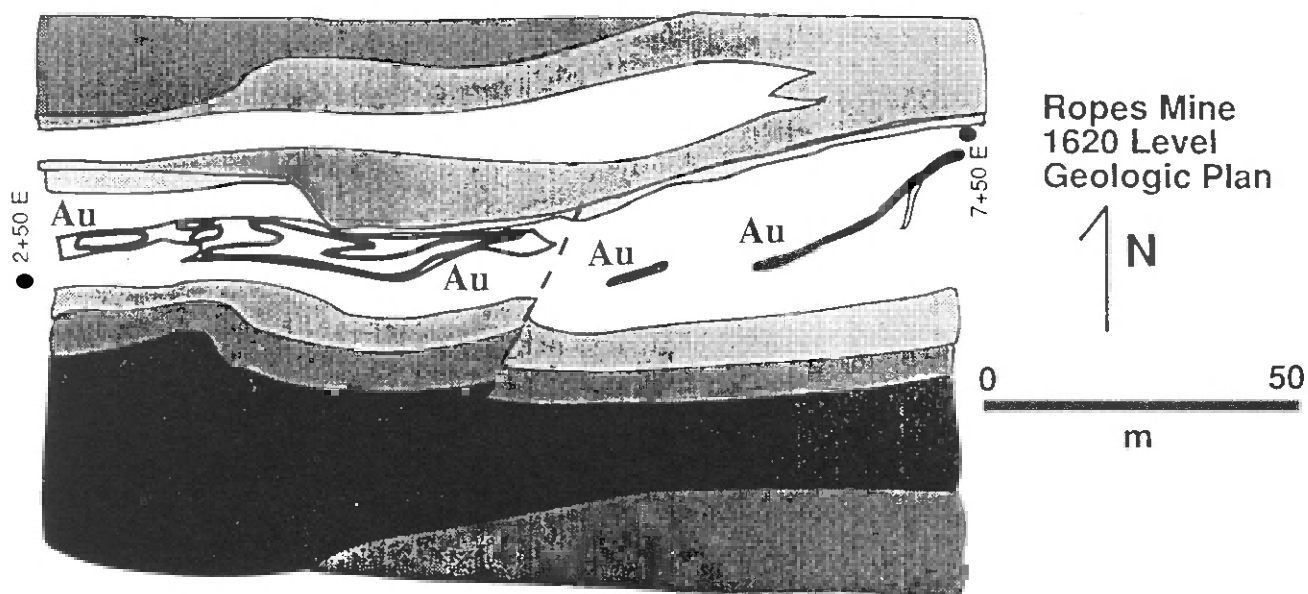
Figure 5: Vertical long section of the Ropes mine in the N80°E showing gold ore subtypes.



ROPES MINE 1152 LEVEL PLAN

- > 4 g / tonne Au ore zones
- quartz - sericite - chlorite rock

Figure 6: Geologic plan map of the 1152 level of the Ropes mine showing high grade ore zones.



EXPLANATION

- | | |
|--|--|
|  serpentinitic peridotite |  > 2 g / tonne Au |
|  carbonate - talc rock |  > 4 g / tonne Au |
|  carbonate - quartz - chlorite rock |  auriferous quartz vein |
|  quartz - sericite - chlorite rock | (Lower Secondary Drift Vein) |
|  microcrystalline carbonate - quartz rock | |

Figure 7: Geologic plan map of the 1620 level of the Ropes mine.

south of the central part of the main ore zone.

Non-Auriferous Veins

Milky white, vitreous, medium to coarse-grained quartz veins commonly cut the east northeast foliation in the quartz-sericite-chlorite rock at a high angle. Some dip steeply, whereas others are shallowly dipping veins offset in north side up stepwise fashion along foliation parallel structures. The veins are not auriferous and are commonly up to 10 cm thick and several meters in length. They are approximately 1% of the quartz-sericite-chlorite rock. Quartz in the veins has full extinction under crossed polars, simple grain boundaries, and locally has minor pyrite.

Banded dolomite veins commonly strike 015° and dip nearly vertical. They cut the auriferous quartz veins. Massive, planar sided, coarse crystalline white dolomite veins up to 10 cm thick cut all other veins and are undeformed.

Structure

An 065° striking near vertical foliation is defined by planar alignment of sericite and chlorite in the quartz-sericite-chlorite rock. This foliation is interpreted as tectonic schistosity or S fabric because the sericite and chlorite are secondary minerals that cut and locally displace relict primary magmatic features, such as domains of former feldspar phenocrysts, and lithic fragments. Locally S-C fabric is developed, especially in carbonate-talc and carbonate-quartz-chlorite rocks.

Contacts between the quartz-sericite-chlorite rock and rocks derived from a peridotite protolith defined planes of weakness that favored development of a shear zone. The orientation of reactivated zones of weakness such as contacts between rock types are not strictly governed by the exact orientation of the stress that causes the movement.

Ore Related Structure

The Ropes main ore zone trends 080° overall, but is internally comprised of 055° to 065° trending zones of greater Au concentration, which host most of the gold. These occur in low angle sigmoidal zones of greater than 4 g/ton Au concentration within ore characterized by dispersed pyrite or in auriferous quartz-tetrahedrite oblique shear veins with similar geometry and orientation.

Zones with greater than 4 g/ton gold concentration₁ defined by assay data, are more centrally within the Ropes main ore zone (Figures 6 and 7). The middle parts of these higher grade zones strike en echelon across the overall 080° trend of the ore body at approximately 055° whereas their extremities nearer the contacts with the carbonate-quartz-chlorite rock strike approximately 070° , forming a low angle sigmoidal pattern across the zone, which is most prominent on the east end of the 1152 level (Figure 6). This geometry is consistent with greater movement being accommodated near the margin of more ductile deforming carbonate-quartz-chlorite rock, where the originally formed 055° to 065° schistosity was flattened to the local 080° plane of shear, represented by the contact between contrasting rock types.

sericite-chlorite rock was encountered in deep drilling at the Ropes deposit, in a zone separate from, and deeper to the east of, the Ropes main ore zone.

Ore Minerals and Textures and Metal Distribution

Gold is with pyrite less than 100 microns in diameter dispersed throughout the mass of the quartz-sericite-chlorite rock, and with this pyrite on fractures, foliations, and within and along the margins of millimeter-thick quartz veinlets. Native gold, of variable fineness, is 1 to 10 micron grains is attached to the surface of the fine grained pyrite, included as round blebs within fine grained pyrite, on fractures within fine grained pyrite, and at grain boundaries of fine grained quartz and sericite. Minor coarse gold is on fractures in quartz veins. Silver is in electrum, native silver is with fine pyrite, argentiferous tetrahedrite, argentiferous galena, and rare dyscrasite.

Pyrite is 97% of the metallic minerals followed by 1% chalcopyrite. Argentiferous galena, argentiferous tetrahedrite, tetrahedrite, sphalerite, millerite, bravoite, magnetite, and rutile are present in trace amounts. The gold is silver bearing and metallic silver is gold bearing. The low bulk Au/Ag of 0.65 for the Ropes gold deposit differs from ratios reported for Precambrian gold-quartz veins and lodes (Boyle, 1979), which range from 1.37 to 12.5 and average about 4.2. Both Au and Ag have continuous positively skewed log normal distributions, each with a single maximum, interpreted as indicating only one period of mineralization.

Distribution. Geometry and Au Concentration of Auriferous Quartz Veins

Auriferous quartz veins are concentrated at the south side of the deposit. Individual veins average 20 cm thick and extend 12 m horizontally and 15 m vertically, but collectively these veins are grouped en echelon, and locally they form ore shoots 8 to 11 m thick, with the quartz veins separated by auriferous foliated quartz-sericite-chlorite rock. The veins strike en echelon at 055° to 065° across the 080° trend of the quartz-sericite-chlorite rock type, dip vertically to 85° south, and have a slight sigmoidal geometry. They occur progressively further east in successively deeper mine levels. Eight major shoots made up of these veins were mined in the 1800's and 1890's above the 800 level. Broderick (1945) implied that single large quartz veins ranged up to 11 m thick, 60 m in horizontal extent, and 76 m vertical extent, but examination of the old mine workings concurrent with development of the modern Ropes mine, and detailed historic descriptions indicate the old stopes were ore shoots made up of a series of smaller individual quartz veins and intervening auriferous foliated quartz-sericite-chlorite rock. The veins are saccharoidal white to light gray quartz, with pyrite and minor argentiferous tetrahedrite, galena, and chalcopyrite; and rare free gold, molybdenite, dyscrasite, tourmaline, and native silver. Overall, metal concentrations in the veins range from 20 to 75 g/ton Au with Au/Ag ratio from 0.08 to 1.76.

The quartz veins have greater concentrations of gold than most of the gold with dispersed pyrite in quartz-sericite-chlorite rock, but the zones of greater than 4 g/tonne Au concentration in the quartz-sericite-chlorite rock are not generally zoned about the veins, rather, they occur more centrally within the quartz-sericite-chlorite rock north of the veins. In some instances, Au concentrations of greater than 4 g/ton in the gold with dispersed pyrite in quartz-sericite-chlorite rock extend along the same 055° to 065° trend eastward from the west end of old stopes which mark concentrations of quartz veins, particularly for old stopes

Vertically dipping, steeply westward plunging auriferous quartz-tetrahedrite veins occur progressively further east in successively deeper levels of the mine. These banded, auriferous, tetrahedrite-bearing quartz veins with aligned schistose inclusions of sericite-quartz-chlorite wall rock are at or near the south side of the main ore zone and have an orientation the same as the zones of schistosity parallel gold concentration with dispersed pyrite, which are more centrally within the trend of quartz-sericite-chlorite rock. The veins are oriented nearly parallel to the schistosity, and therefore nearly perpendicular to the inferred maximum principal stress. They contain schistose septa identical in composition to the quartz-sericite-chlorite wall rock and have quartz with undulose extinction and subgrain development textures indicating grain size reduction. These characteristics are compatible with an origin as oblique shear veins formed in the direction of shear movement (Hodgson, 1989). Oblique shear veins are inclined to shear zone margins in the same way as P shears and show the same sense of en echelon stepping as the sense of movement across the zone containing them (Hodgson, 1989). In the case of the Ropes deposit, this indicates a dextral component in plan view. An origin for the quartz-tetrahedrite veins, and the en echelon zones of Au concentration with dispersed pyrite, as tension shears, extension veins, or Riedel shears in a sinistral shear zone is not indicated because the low angle orientation of the tips of the veins with respect to the shear zone margin, and the similar orientation of the ends of the en echelon zones of Au concentration with dispersed pyrite, is not consistent with the sense of rotation expected in sinistral shear.

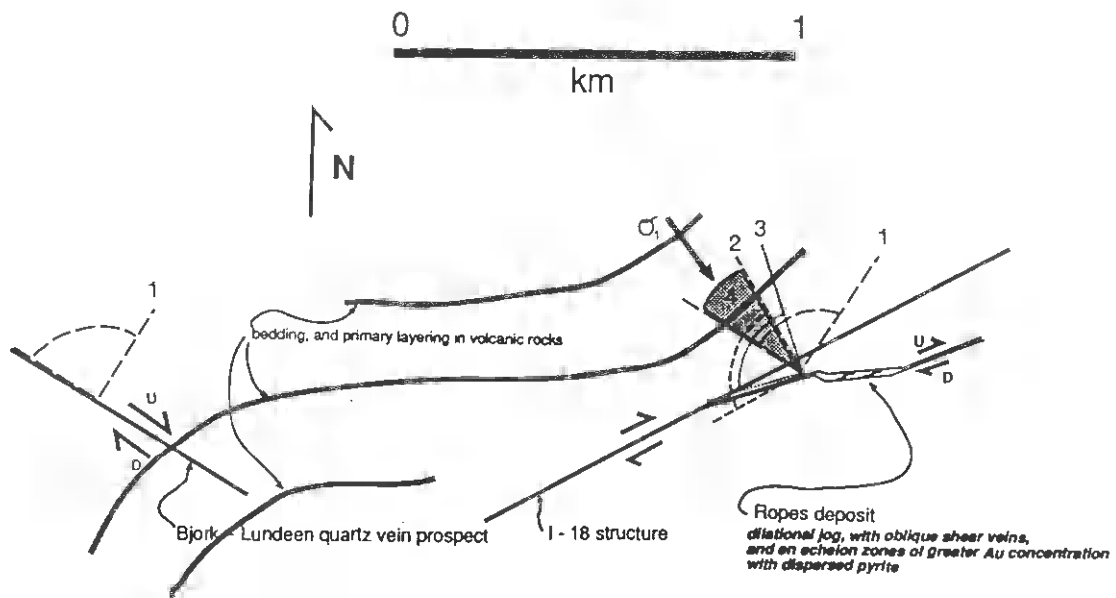
The sigmoidal zones of gold concentration with dispersed pyrite and the oblique shear veins have orientations nearly parallel to the S fabric, consistent with an origin as P shears. P shears commonly form at approximately 10° to the shear zone boundaries, after peak deformation, when resistance to shear is decreased by the presence of well developed planar fabric (Tchalenko, 1970).

Inferred Direction of Shear

Movement direction in a shear zone is commonly considered to be in the line perpendicular to the intersection of the shear zone margin with the plane of the oblique S fabric, and the sense of movement is inferred from the sense of obliquity of the fabric to the shear zone margin. In a ductile environment the acute angle between the S fabric and the shear plane faces away from the direction of movement. The sigmoidal zones of greater gold concentration with dispersed pyrite follow an S fabric, interpreted as a largely compressive, ductile feature. Contacts with nonfoliated serpentinitic peridotite north and south of the Ropes deposit are considered shear planes parallel to the C direction. The orientation of the S fabric relative to the C direction indicates a dextral component of movement when viewed in the horizontal plane, with the south side of the zone moving west southwest and the north side moving east northeast. (Figure 8). Offsets along northeast trending faults in the deposit, and the Z sense of warping of layering between the rock types at the south side of the deposit (Figure 7) also support a dextral component of movement.

Localization of the Deposit Within a Dilational Jog

The trend of quartz-sericite-chlorite rock strikes 070° overall but 080° where it hosts the main ore zone (Figure 8). This 080° part of the trend acted as a dilational jog or releasing bend during the indicated dextral component of movement in plan view (Figure 8). Releasing bends are commonly sites for ore deposits, even if the main fault trend is barren



Numbered quadrants marked by dashed lines are ranges of possible orientations of horizontal components of maximum principal stresses which could account for dextral components of strain at:

1. Bjork - Lundeen prospect
2. I - 18 Structure
3. Ropes deposit
4. Possible range of horizontal component of maximum principal stress which could simultaneously satisfy requirements for sites 1, 2, and 3 above

Figure 8: Structural model for the Ropes mine.

(Sibson, 1987). Both the sigmoidal zones of Au concentration with dispersed pyrite, and the auriferous quartz veins are interpreted as indicating local extension within a dilational jog. There is a component of positive volume change in the shear zone, in an otherwise compressive tectonic regime. Increased pore pressure within the shear zone as microfractures filled with fluid, combined with the extensional effect of the dilational jog, may have contributed to local extension. Slip transfer in dilational jogs involves extensional fracture openings localized in the jog, or step over. Formation of dilational jogs involves local loss of cohesion, or brittle failure, in an otherwise ductile environment.

The trend of quartz-sericite-chlorite rock which hosts the Ropes main ore zone narrows to the east of the deposit, as well as toward surface up dip from the deposit, where it bends from a near vertical dip at depth to a 70° south dip at shallow levels. This change in thickness and attitude may have caused barrier conditions for ascending hydrothermal fluids, resulting in another control on localization of ore in addition to the dilational jog controlling of the overall setting of the deposit.

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Geologic Field Excursion to the Ishpeming Greenstone Belt

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Introduction

This geologic field excursion to the Ishpeming greenstone belt consists of 8 selected stops (Figure 1). These stops are designed to cover the major varieties of volcanic lithologies found in the belt and several localities of structural significance. Johnson and Bornhorst (this volume) provide an overview of the greenstone belt and explanation of stratigraphic terminology used in this guide. A detailed topographic map is provided to identify the location of the stops, however users should refer to larger scale maps in order to navigate roads to the stops.

Field Trip Stops

Stop A - Lighthouse Point

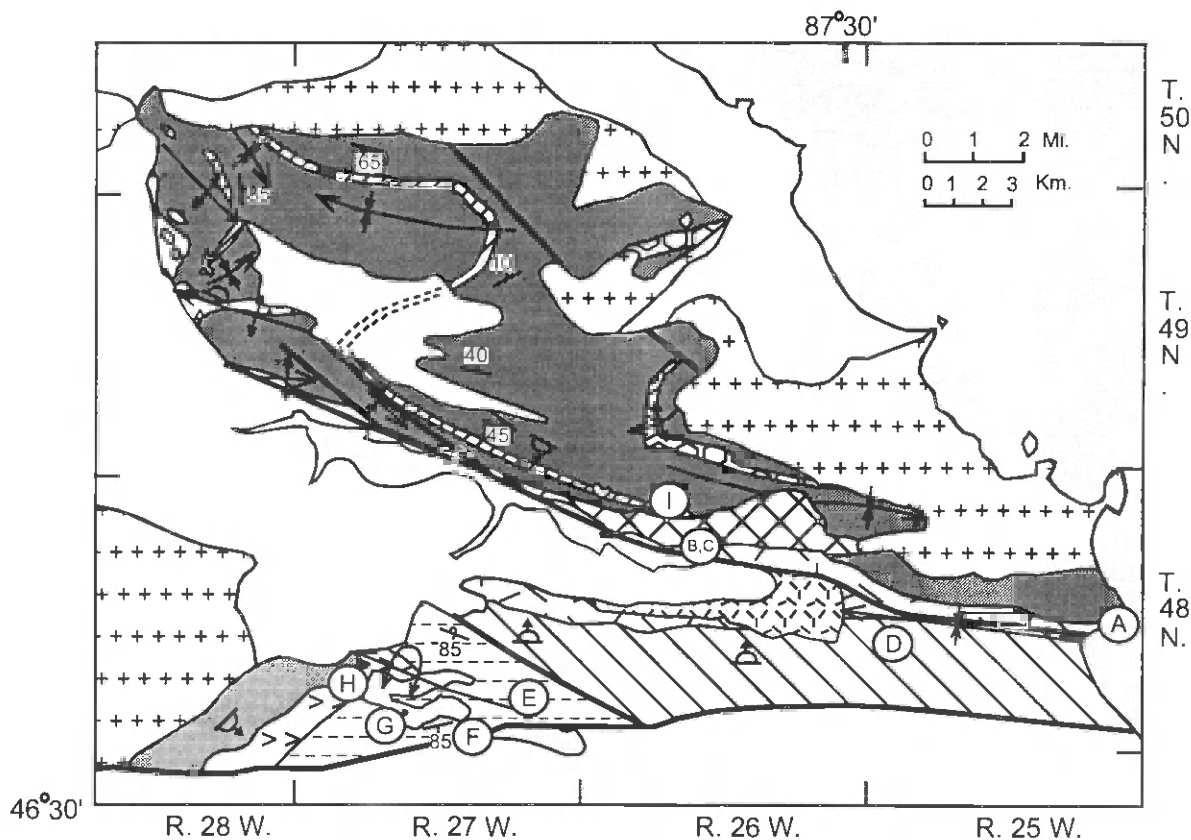
Purpose: View: 1) amphibolite schist of Lighthouse Point Basalt, 2) Dead River Shear Zone, and 3) cross-cutting relationships of Archean and Proterozoic rocks (Figure 2).

Note: You must obtain permission from the U.S. Coast Guard to visit this locality. No rock hammers or specimen collecting are allowed at this stop. Park in the parking lot across from the Coast Guard office.

At this stop excellent shoreline exposures on Lighthouse Point and along the adjacent beach provide a view of Archean and Proterozoic rocks (Figure 3). Gair and Thaden (1968) mapped these rocks in detail.

Part I. The outcrop in the middle of the beach near the parking lot is composed of Archean thinly layered, amphibolite schist (basalt). The basalt here is part of the Lighthouse Point Basalt. The layers on Lighthouse Point generally strike E-W and dip 70°N. The layers in the basalt are interpreted as highly flattened pillows. The flattening is interpreted to be a result of north verging recumbent folding (Johnson and Bornhorst, 1991).

Part II. The outcrop on the southwest end of the beach is composed of chlorite-sericite schist, again part of the Lighthouse Point Basalt (see Johnson and Bornhorst, this volume). The chlorite-sericite schist is interpreted to be deformed pillow basalt and are metamorphosed to greenschist facies. Kinematic indicators (S-C fabric in particular) indicate a dominantly left-lateral shear sense, but on close inspection right-lateral and north-side-up indicators are also present. This locality is interpreted to be the eastern extension of the Dead River Shear Zone that separates the northern block of the Ishpeming greenstone belt from the southern two blocks (Figure 1).



Explanation

Proterozoic

□ Sedimentary rocks

Archean

Intrusive Rocks

▨ Granodiorite

▨ Tonalite

▨ Deer Lake Peridotite

Sedimentary Rocks

▨ Timiskaming-type sedimentary rocks

Volcanic Rocks

Lighthouse Point Basalt

▨ Basalt

▨ Reany Lake pyroclastic unit and
Fire Center mine iron-formation unit

▨ Nash Creek glomerophytic basalt unit

Mona Formation

▨ Upper tuff unit and lapilli-tuff unit

▨ Basalt flow unit

Kitchi Formation

▨ Tuff unit and lahar unit

▨ Basalt flow unit

85 ▨ Bedding

87 ▨ Overturned bedding

▨ Facing of pillows

▨ Plunging anticline

▨ Plunging syncline

▨ Plunging overturned anticline

▨ Shear zone

⊙ (A) Location of stops

Figure 1: Generalized geologic map of the Ishpeming greenstone belt showing location of stops.

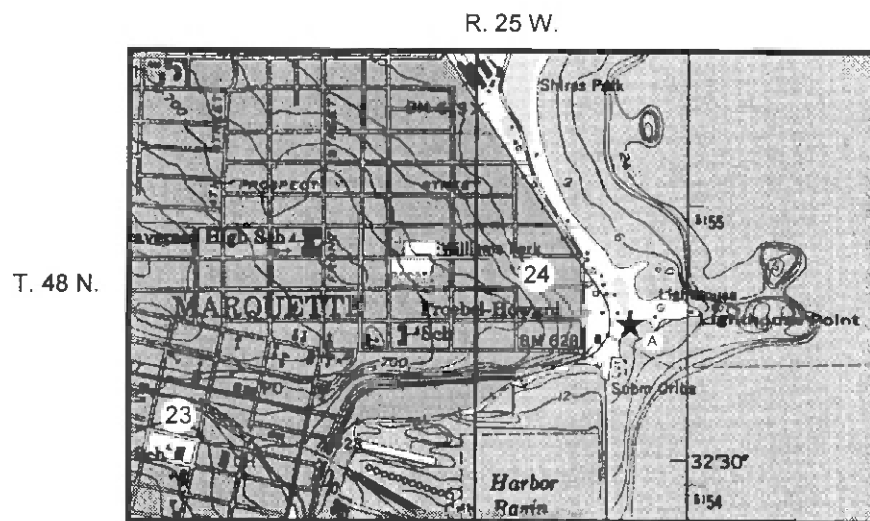
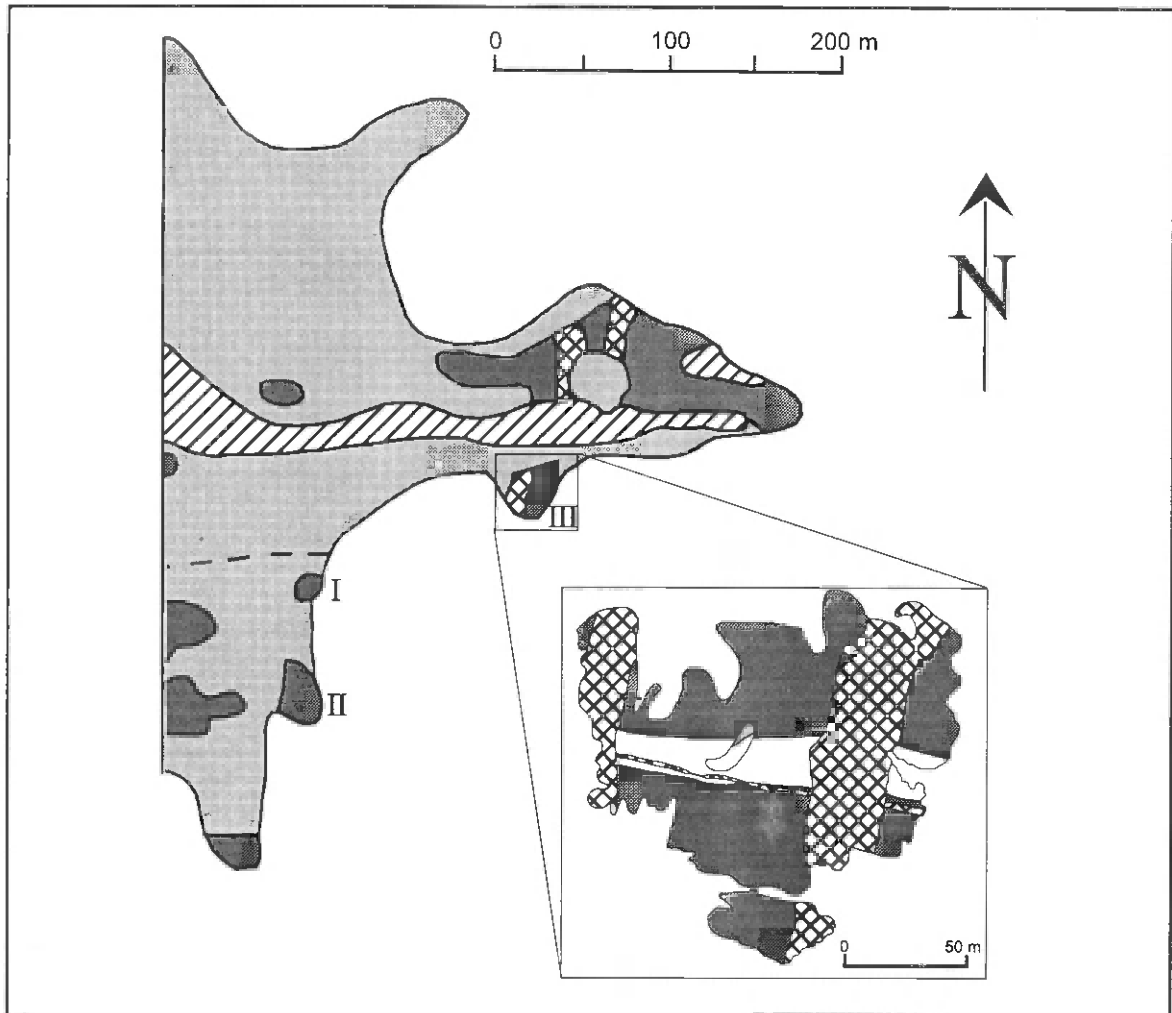


Figure 2: Stop A- Lighthouse Point



Explanation

Middle Proterozoic

 Keweenaw diabase dike

Early Proterozoic

 Metadiabase dike

Archean

Intrusive Rocks

 Rhyolite

Lighthouse Point Basalt

 Basalt, outcrops in darker shade

Figure 3: Geologic map of Lighthouse Point (modified from Gair, 1959).

Within the basalt dominated outcrop there are lenticular pods of quartz-chert (hematite stained) and small texturally different quartz veins. The interpretation of the quartz-chert pods is not clear, they could be synchronous with deposition of the basalts. Small quartz veins are found in rocks throughout the Ishpeming greenstone belt. Most of these were likely emplaced during Archean deformation and metamorphism. However, at least some were emplaced during the Proterozoic (Bornhorst and others, 1998).

Part III. The main outcrops of Lighthouse Point are northeast of the first two localities. This trip will only visit the shoreline outcrops on the northeast end of the beach, near a house. Here, Archean thinly layered, amphibolite schist (basalt) is cut by a tabular, porphyritic rhyolite dike trending roughly parallel to the layering. The layered basalt is part of the Lighthouse Point Basalt and the rhyolite is interpreted as synchronous with the synorogenic late trondjemite-granite suite plutons that reorient earlier fabrics.

The Archean rocks are cut by two N-S trending Proterozoic diabase dikes that are metamorphosed to greenschist facies as compared to the surrounding Archean rocks that are metamorphosed to amphibolite facies. The crest of the ridge (not visited today) is underlain by a relatively unmetamorphosed E-W trending diabase dike of Keweenaw age.

Stop B - White Bear Drive

Purpose: View the upper tuff unit of the Mona Formation and S_3 crenulation cleavage (Figure 4).

The rocks at this stop are part of the upper tuff unit of the Mona Formation. The rocks of the upper tuff unit consist of quartz-feldspar-sericite-chlorite schist. Thin primary layering sub-parallel to S_1 foliation can be observed in some of the outcrop in this area. Based on the presence of sand-sized, lenticular volcanic fragments, and lack of sand-sized quartz and feldspar in an intact framework, most of these schist beds are interpreted as tuff.

On the north side of the outcrop nearest White Bear Drive we can see the hinge of a westward plunging F_3 fold. This allows us to see S_3 crenulation cleavage. On the limbs of the fold S_1 and S_3 are parallel and indistinguishable (see Johnson and Bornhorst, this volume, Table 1).

Stop C - Tower

Purpose: View the lapilli-tuff unit of the Mona Formation and S_3 crenulation cleavage (Figure 5).

Note: Park at the communication tower and walk about 100m downhill in a southerly direction to a series of outcrops alongside the hill.

The rocks at this stop are part of the lapilli-tuff unit of the Mona Formation. The rock is composed of calc-alkalic rhyolite lapilli in a quartz-sericite-chlorite matrix with quartz and

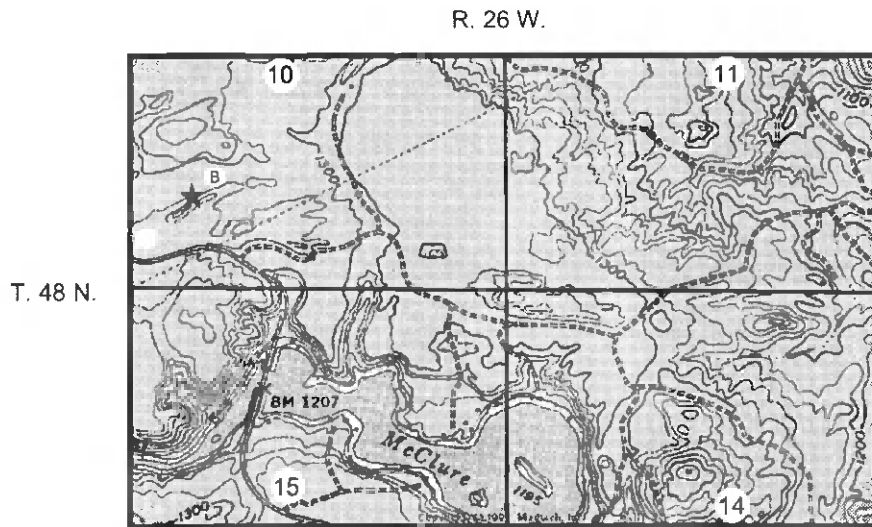


Figure 4: Stop B-White Bear Drive

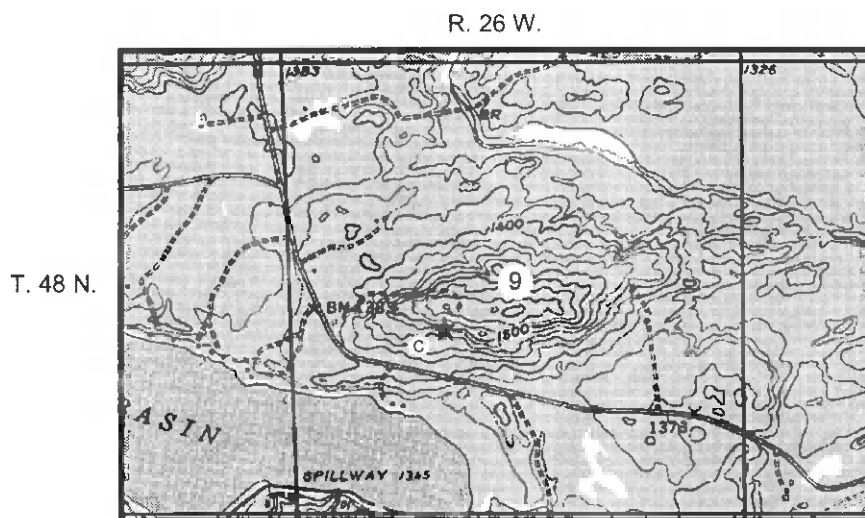


Figure 5: Stop C-Tower

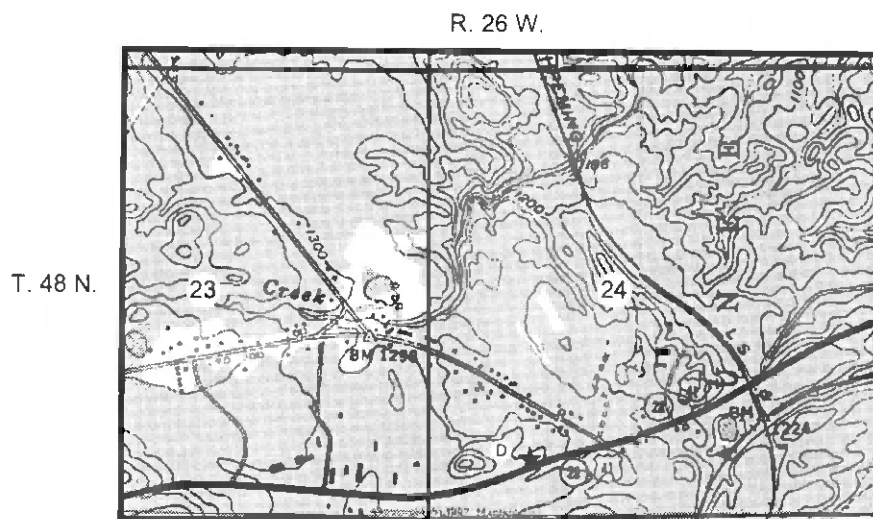


Figure 6: Stop D-Shunk Furniture

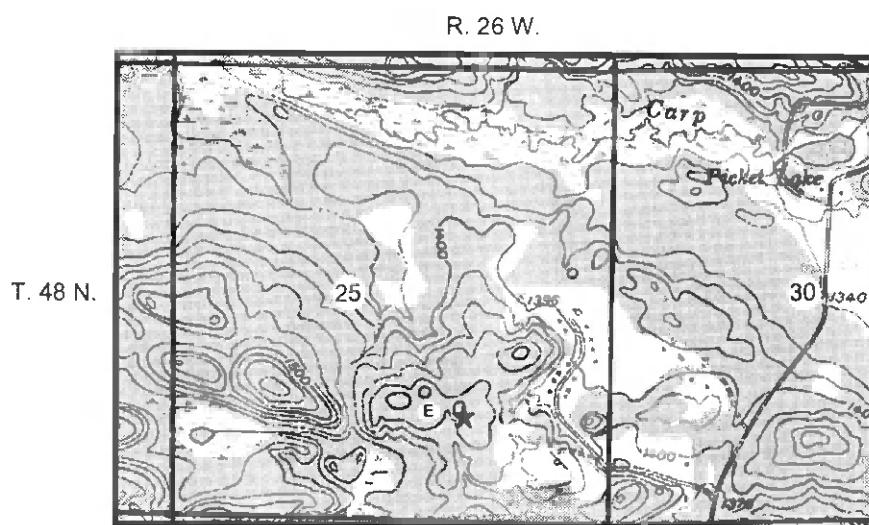


Figure 7: Stop E-Tuff Unit of the Kitchi Formation

less commonly, feldspar phenocrysts. Flattened apple green lapilli (muscovite and chlorite; Puffet, 1974) are also common at this stop. This unit is interpreted as subaqueous pyroclastic flow and fall deposits.

At this stop an earlier shallowly easterly dipping foliation (S_1) is crenulated by a later E-W trending foliation (S_3). The lapilli are flattened along the S_1 foliation and elongated in the direction of the intersection of S_1 and S_3 . The Dead River Shear zone (D_2 , D_4) is interpreted to be located on the north side of the tower hill.

Stop D - Shunk Furniture

Purpose: View pillowed basalt of the Mona Formation (Figure 6)

Note: Park alongside of the road across from Shunk Furniture, but be very careful of traffic.

There are excellent views of relatively undeformed pillowed tholeiitic basalt in outcrops alongside of U.S. The pillowed basalts are part of the basalt flow unit of the Mona Formation. The pillows are ellipsoidal in shape with dimensions about 30 cm X 1.5 m; attitude of bedding strikes approximately E-W and dips 85° N. Cusps on pillows indicate that stratigraphic top is to the north. There are characteristic well-developed pillow rinds, radial fractures, and inter-pillow void spaces filled with quartz and carbonate. Overall, pillowed and massive tholeiitic basalt is the dominant lithology in the Ishpeming greenstone belt.

Stop E – Tuff Unit of the Kitchi Formation

Purpose: View tuff unit of the Kitchi Formation and evidence for superposed folding (Figure 7).

At this stop we will see some of the lithologic variation within the tuff unit of the Kitchi Formation and evidence for large scale folding. Cross-bedding, graded bedding, and cut and fill structures are uncommon in the Kitchi Formation, but in this area clearly indicate tops to the east. A foliation at right angles to bedding indicates this area is near a vertically plunging fold nose.

Stop F - Teal Lake

Purpose: View the Carp River Falls shear zone, tuff unit of the Kitchi Formation and Ajibik Quartzite of the Menominee Group of the Marquette Range Supergroup (Figure 8).

At this stop we will cross the Carp River Falls shear zone from Lower Proterozoic metasedimentary rocks into Archean metavolcanic rocks. We will begin the traverse in the relatively undeformed steeply dipping Ajibik Quartzite of the Lower Proterozoic Marquette Range Supergroup. The Carp River Falls shear zone is a high strain zone indicated by quartz-sericite-feldspar-chlorite schist. The foliation in the schist is near vertical and has a steep mineral lineation. As the shear zone is traversed there is a noticeable increase in the

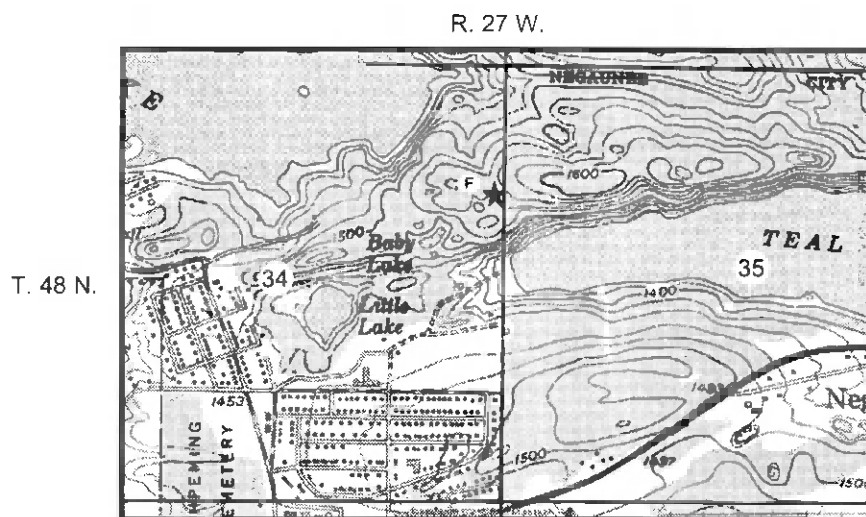


Figure 8: Stop F-Teal Lake

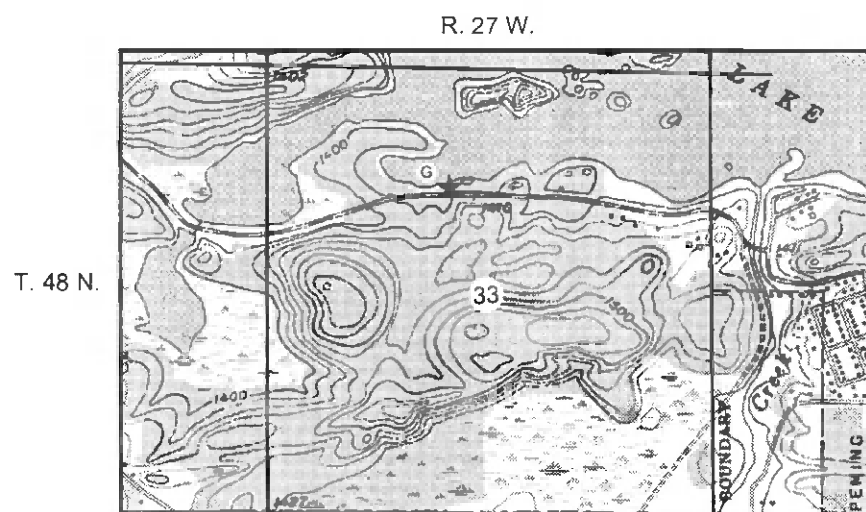


Figure 9: Stop G-Along Deer Lake

amount of chlorite in the schist. On the north side of the Carp River Falls shear zone is quartz-feldspar-sericite-chlorite schist of the tuff unit of the Kitchi Formation.

Stop G - Along Deer Lake

Purpose: View lahar unit of the Kitchi Formation (Figure 9).

At this stop polymictic volcanic conglomerate is exposed in a glacially polished outcrop along the north side the road towards Deer Lake. Park alongside of the road. This volcanic conglomerate is part of the lahar unit of the Kitchi Formation. On the polished surface, the volcanic clasts vary from 25 cm X 35 cm in cross section, down to the size of the matrix grains. Larger clasts, up to 60 cm X 1.2 m in cross section, are present in the nearby lake shore outcrops. Clasts greater than 1 cm 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 volcanic clasts are calc-alkalic andesite to dacite in composition with most clasts at this locality being near the andesite to dacite division with small chemical variation (Bornhorst unpublished data). Most clasts are porphyritic and some are holocrystalline. The volcanic conglomerate is interpreted as a subaqueous lahar deposit.

Stop H - Shoreline of Deer Lake

Purpose: View Deer Lake Peridotite (Figure 10).

Note: There is a small pullover on the east side of the road. Park and walk along the road to the north where you can find a small trail that leads through the woods to the tip of the point.

Outcrops occur along the shoreline of this small point into Deer Lake. At this stop serpentized peridotite of the Deer Lake Peridotite is exposed along the shore of Deer Lake. Elongate pods of massive serpentized peridotite with closely spaced fractures are surrounded by 2 to 5 cm wide ribbons of 1 to 2 mm subparallel veins of cross cross-fiber serpentine (Bornhorst and others, 1986). The dark grey to green massive serpentized peridotite is fine- to medium-grained and lacks obvious foliation. In hand sample one can find well-developed 1 to 5 mm pseudomorphs after olivine and pyroxene outlined by thin selvages of white carbonate or talc. No spinifex or pyroxene "string beef" textures indicative of komatiite flows have been found. The chemical composition indicates an olivine to pyroxene ratio from about 0.25 to 2 and most samples are in the harzburgite field and some are in the lherzolite field. The Deer Lake Peridotite is interpreted as a sill complex.

This locality is only a few 100 meters from the Ropes gold mine. The shear zone that hosts the Ropes gold mine projects immediately north of this small point. The serpentized peridotite has a strong, contorted foliation with magnetite as irregular veinlets and streaks along the foliation planes indicating the shear zone that hosts gold at the Ropes mine continues into the Deer Lake Peridotite. Adjacent to the gold ore body the serpentized peridotite is altered to a talc-carbonate rock (Bornhorst and others, this volume).



Figure 10: Stop H- Shoreline of Deer Lake

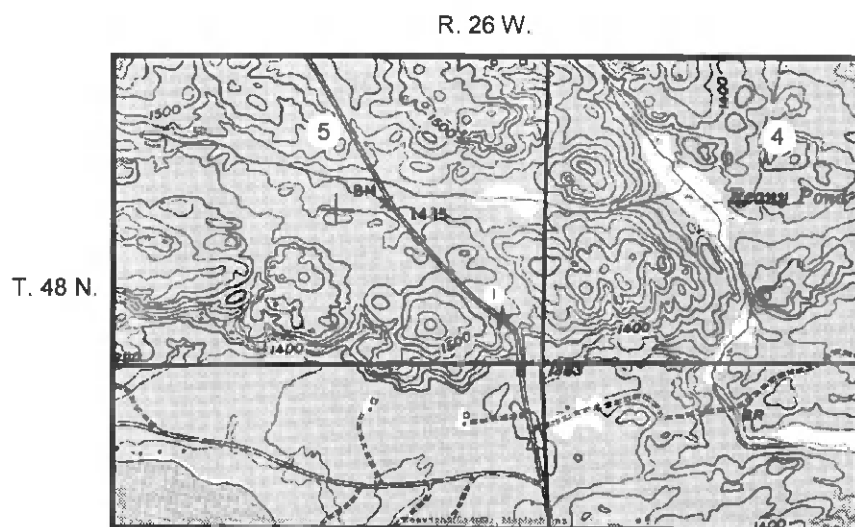


Figure 11: Stop I- County Road 510

Stop I - County Road 510

Purpose: View fire Center Mine iron-formation of the Lighthouse Point Basalt (Figure 11).

Note: Park alongside of the road, but be careful to watch for logging trucks moving at high speeds.

There are several outcrops on both sides of County Road 510 at this stop. The particular outcrop of interest is near the top of the slope on the east side of the road, it may take a little effort to find the iron-formation. At this stop the Fire Center Mine iron-formation unit of the Lighthouse Point Basalt is overlain and underlain by massive tholeiitic basalt of the Lighthouse Point Basalt. The iron-formation is approximately 1.5 m thick and strikes N30°W. It is composed of fine, black chert that contains scattered magnetite grains and pyrite. To the west of this locality, the iron-formation is layered with 1.5 cm thick chert and magnetite bands. Despite variable magnetite content, this iron-formation produces a strong magnetic signature and can be traced from north to south in this stratigraphic block of the greenstone belt. This iron-formation is an excellent stratigraphic marker. The basalt is dark green to black, fine-grained and relatively non-foliated and metamorphosed to amphibolite grade.

Acknowledgments

We thank Shannon E. Bair for computer drafting of the figures.

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**Shear Zones and Gold Mineralization
in the South Half of the Ishpeming Greenstone Belt,
Michigan**

by

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Foreword

Much of this field trip is devoted to gold occurrences. At most stops, the guidebook descriptions will include the results of sampling and assaying for gold. The term “grab sample” means a small reconnaissance-style sample deliberately chosen by an exploration geologist to have, in his experience, the maximum chance of yielding gold in the assay because of the presence of alteration, sulfides, gossan, etc.. If our reported result contains gold, this doesn't necessarily mean that someone else's subsequent sample will give the same value. This phase of sampling is deliberately subjective, and gold distribution is far from uniform in Archean deposits, varying greatly within small domains, even at producing mines. More representative sampling will be discussed at some of the field trip stops as either “channel” or “chip” samples across an exposure. Channel samples, taken either from diamond blade rock saw cuts or hand-cut by hammer and moil, are meant to be volumetrically equivalent to a ½ split of BQ (1.5-inch diameter) drill core. Chip samples are more representative of the exposure than a grab sample, but not as rigorously taken as a channel sample.

Unless otherwise specifically noted, all gold values reported herein are from samples crushed, ground, split and assayed at the former Callahan Mining Corporation assay lab in the Humboldt (Ropes) Gold Mill, now owned and operated by Minerals Processing Corporation (MPC). MPC's assays were all done by the fire assay-gravimetric finish method, using a 1-assay ton (29.167 gram) subsplit. MPC's lower detection limit by this technique is .003 oz/ton (103 ppb) Au. The terms “no gold”, or “below detection” refer to this limit. In some cases where we felt it important to know the presence of even lower Au values, separate subsplits were sent to Chemex Labs in Vancouver, B.C. for analysis by a lower detection limit technique, noted herein where so done. This technique is the fire assay - atomic absorption finish process (FA-AA), and has a lower detection limit of 10 ppb.

Chemex Labs also performed whole rock major oxide analyses. Results from samples taken at some of the field trip stops are shown on Jensen cation plots (Grunsky, 1983; Jensen, 1976) that have been routinely used for characterizing the lithochemistry of the rocks from this region (Bornhorst and Johnson, 1993). Figure 1 is a template Jensen plot. The Jensen plots were done by consulting geologist R.A. Campbell, Burlington, Ontario, using “Newpet” software developed and distributed by the Earth Sciences Department of Memorial University of Newfoundland. Mr. Campbell's assistance is gratefully acknowledged.

Chemex also did a 32-trace element analysis using the X-ray fluorescence technique for all samples submitted for assay; results are discussed where significant.

All petrographic descriptions are from polished thin sections examined with the assistance of R.L. Barnett of Barnett Geological Consulting, London, Ontario. Mineral compositions were determined using Barnett Geological's JEOL Model 733 five spectrometer scanning electron microprobe. Mineral percentages are visual estimates; no point counts were done. Mr. Barnett's valuable help is also gratefully acknowledged.

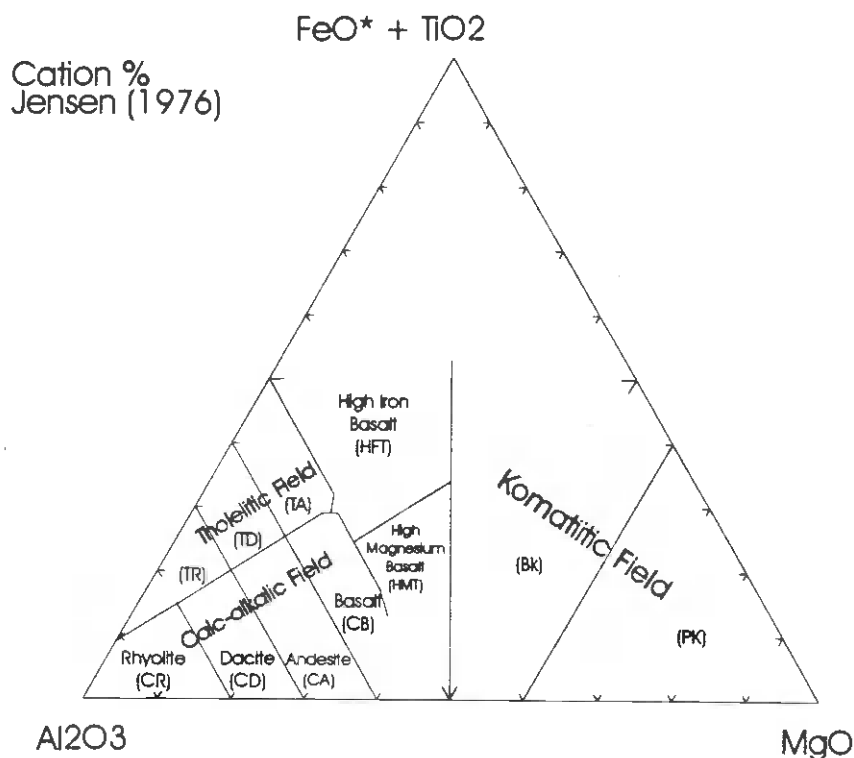


Figure 1: Fields for the Jensen Cation Plot

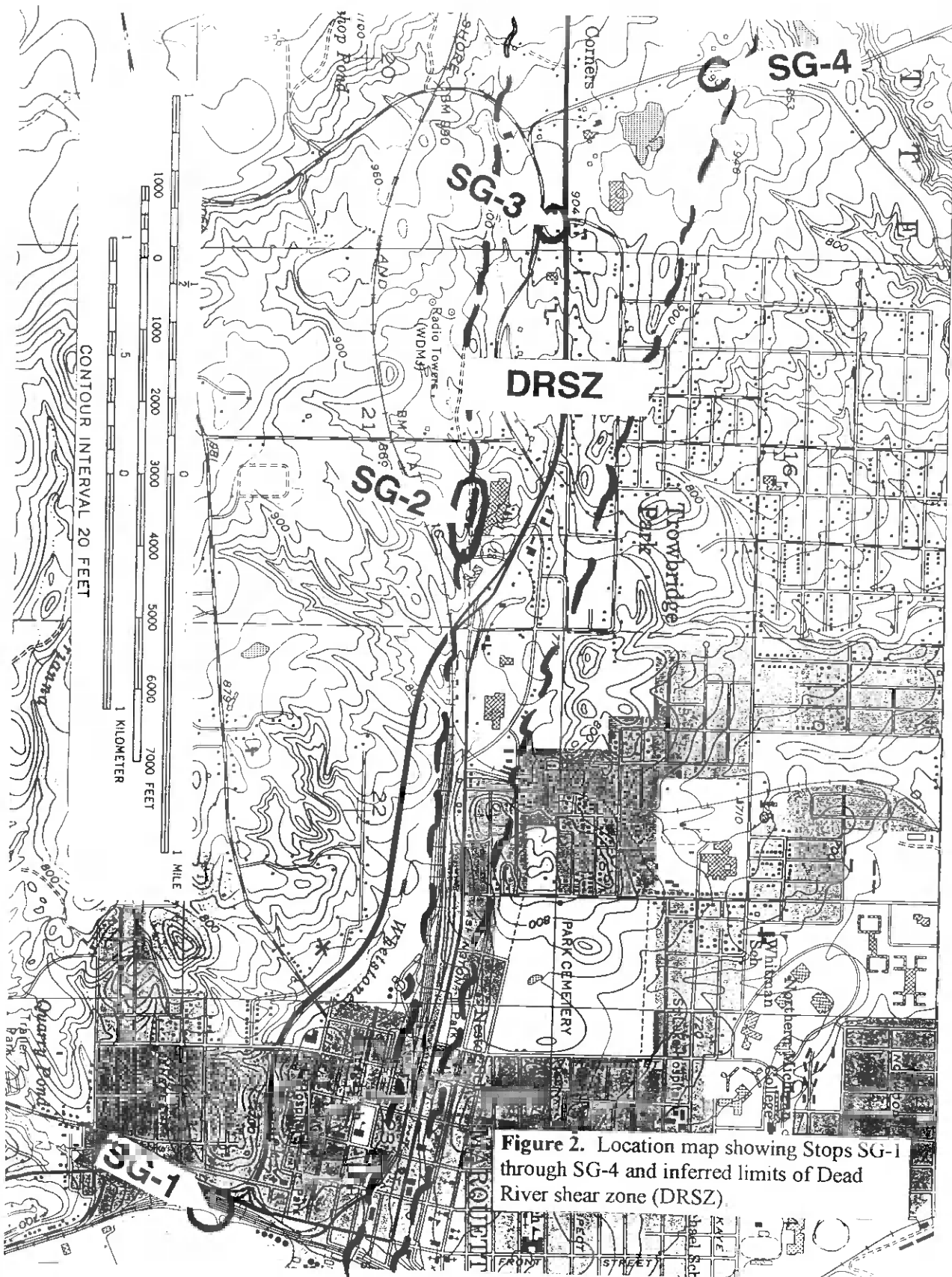


Figure 2. Location map showing Stops SG-1 through SG-4 and inferred limits of Dead River shear zone (DRSZ).

**Stop SG-1: Variably sheared pillow basalt of Mona Formation near Marquette Harbor
(Location map, Figure 2).**

Gair and Thaden (1968) last mapped this locality and assigned it to the lower member of the Mona Schist. Recently Bornhorst and Johnson (1993) have revised the stratigraphic nomenclature of the Ishpeming Greenstone Belt; this locality would now be assigned to the informal basalt flow of the Mona Formation, its lowermost unit. Pillowed metabasalts of greenschist facies are the predominant lithology in this unit.

The exposures here are best seen in a three-part sequence. After parking in the abandoned railroad yard, head east and take the trail along the south side of Whetstone Brook to the lakeshore to see glacially polished outcrops of pillow lavas. The outcrops display well preserved glacial grooves and striae trending 198°; some of the grooves contain classic examples of crescent-shaped chatter marks pointing down-ice.

The two outcrops here show a layer of massive non-pillowed basalt conformably sandwiched between two pillowed layers. The layering shown by this "sandwich" trends approximately 305°. The pillows are pristine and undeformed, some of them up to six feet across. They display internal cooling fractures, well preserved rinds, and cusps consistently showing tops to the north.

The next point of interest is about 100 feet south on the rocky point of the lakeshore. Please be careful while making your way southward over this slippery outcrop. On the south side of this rocky point are pillowed basalt and thin discontinuous lenses of chert interbedded with the pillows, some forming pillow selvages. Some of the chert contains patches of brecciated red jasper; this texture is probably the result of soft sediment deformation. None of these cherts is magnetic. A great deal of excess calcite is also present with the pillows. This probably contributed to the development of shearing, which can be clearly seen to be increasing rapidly in intensity southward in this outcrop. We think that the calcite and chert lenses are the result of degassing and seawater precipitation in and near a flow top. In our experience such interpillow zones containing discontinuous thin cherts are very common.

Taking the path from the beach westward back to the railroad yard the progressive deformation of pillow basalt here is perhaps best seen. Entering the yard, the outcrop exposure on the right (north) again marks the north edge of the developing shearing. Here the rock is moderately and variably sheared but the outlines of pillows can still be seen despite a penetrative foliation striking 290°, 85°N (photo, Figure 3). The pillow rinds are pinkish weathering calcite, and the pillows here are much smaller than those earlier seen to the north, again a possible contributing factor to the development of shearing here.



Figure 3. Looking northwest at sheared greenstone outcrop on east side of rail yard, Stop SG-1. Hammer point touching calcareous flattened pillow rind.

Moving west across the railroad yard, the third part of this stop is its west wall. The features here are more continuously exposed about 50 yards west of here and above us in the U.S. Highway 41 road cut; that is a very dangerous high speed traffic location and we've chosen to show the same units in detail at this rail yard exposure instead.

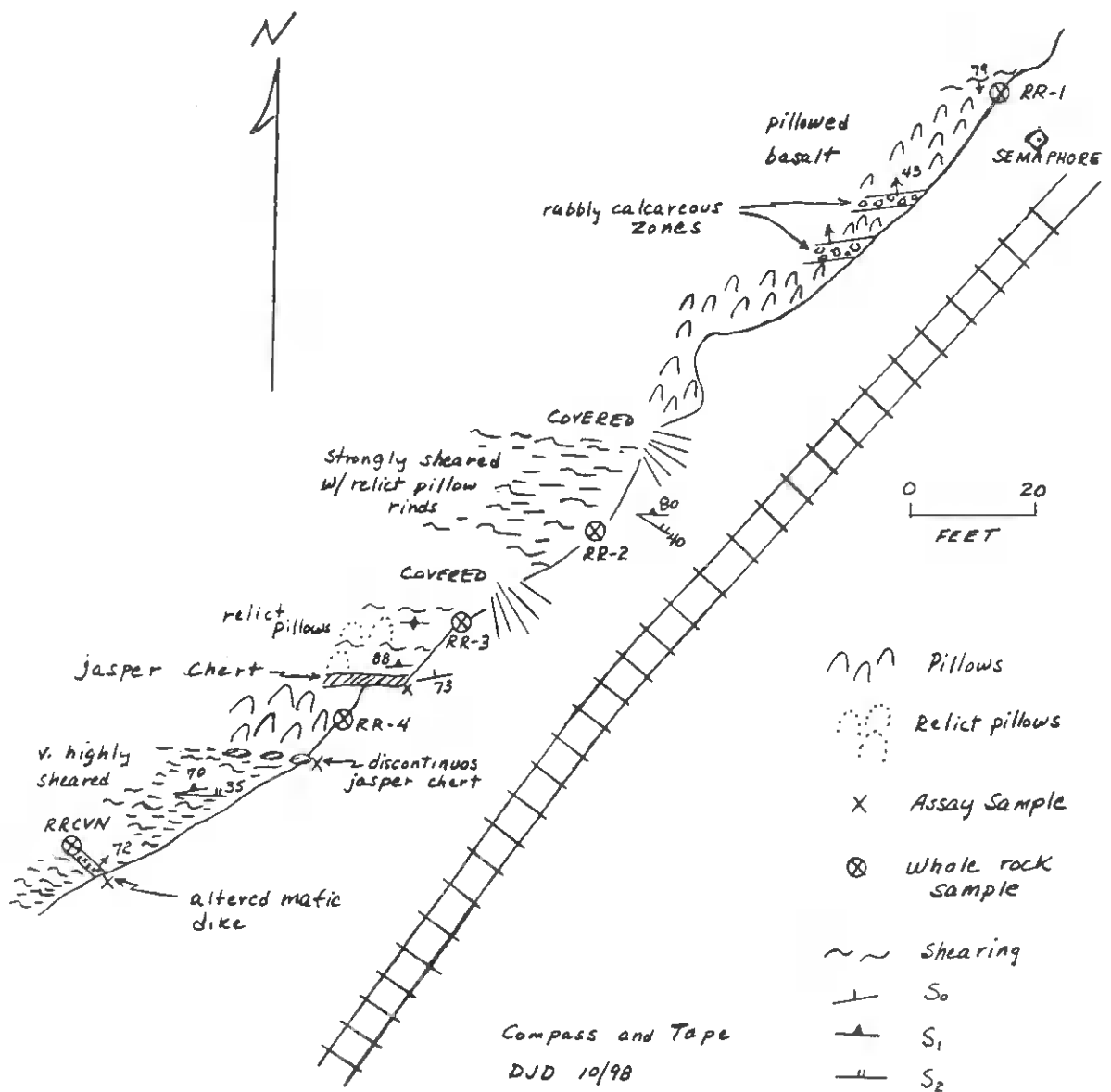


Figure 4. Compass and tape map of west wall of railroad yard, Stop SG-1.

Figure 4 is a map of the rail yard exposure. From north to south, the first exposed unit is dark blackish green non-amygdaloidal pillowed basalt with calcareous epidote-rich pillow rinds. The pillows are quite large, some up to four feet across. Blobs of calcite and calcite-cemented breccia fill some of the pillow interstices. Within this unit there are shallow north-dipping rubbly zones that may represent irregular flow tops. Many of the pillow cusps indicate facing to the north, but this is easily arguable at this outcrop. The pillows themselves are not megascopically foliated.

Moving southward, there is an 8-foot covered interval critical to the relationship between the pillowed basalt and the next unit. In the Highway 41 exposure to the west, this zone is occupied by a sheared-off lens of gray chert and highly sheared rusty weathering chlorite rock with abundant oxidized fine cubic pyrite along shear planes. (grab sample HIWAY-1, .013 oz/ton Au). The remainder of the unit, exposed past the covered interval here, is highly sheared and light gray-green, with a strong S_1 foliation striking 269° , 80°N , defined by chloritic slip planes with vertically plunging lineations. Oblique to S_1 and dipping more shallowly to the north are discontinuous blobs of white calcite and feathery seams of light brown ankerite. These appear to be flattened and sheared-out pillow rinds. Both textural features are cut by a tensional cleavage conjugate to S_1 , striking approximately 300° and dipping 30° - 40°N , defined by thin fibrous calcite seamlets. There are also wide spaced flat-dipping relief fractures with fibrous calcite.

At first sight this rock might be taken for a mafic tuff. However, it lacks definitive features of such a protolith, i.e., lapilli, crystals, lithic fragments or bedding. Instead, it appears to have been derived from shearing of massive rock, save for the relict pillow rinds, which here indicate that the pillows were quite small and probably more susceptible to shearing than the more massive large pillows to the north.

Southward there is another 10-foot covered interval. In the Highway 41 exposure to the west, a highly sheared rusty sericite-chlorite-ankerite zone with traces of oxidized cubic pyrite occupies this. (grab sample HIWAY-2, .009 oz/ton Au). Past this covered interval, the exposure is of moderately sheared gray-green rock. S_1 foliation is approximately 270° , vertical; the shallow dipping cleavage is weakly developed. Blobs of chlorite in the plane of S_1 show vertical alignment, and the rock carries disseminated coarse cubic pyrite with vertically aligned calcite pressure shadows; in thin section both of these exhibit porphyroblastic development, rather than a pre-existing textural fabric. This chlorite-spotted unit has a higher MgO content than the adjacent rocks, plotting in the komatiitic field (see Jensen cation plot, Figure 5).

Further south within this sheared rock is a 1.5 -foot bed of non-magnetic jasper chert that almost surely defines an original layering (S_0). It strikes 285° , dipping 73°N . The patchy bright red jasper zones

in this chert are brecciated in places, as seen in the outcrop east across the railroad tracks. The chert is not foliated, but carries a trace of fine cubic pyrite on late white quartz fractures. A grab sample here yielded .003 oz/ton gold ; FA-AA re-analysis by Chemex gave 51 ppb Au.

Good examples of relict pillows are a couple of feet north of the hanging wall of the chert. This sheared lithology grades southward into non-foliated pillowed basalt. The basalt's southern contact is a thin discontinuous 0-4" non-magnetic chert-jasper breccia that gave no gold in a grab sample. This foliation-resistant pillow basalt unit is about 15 feet thick. Beyond its cherty southern contact the remainder of the exposure consists of highly sheared, light gray-green rock with arguable relict pillow textures, S_1 at 260° , $70^\circ N$. Within this southernmost part of the exposure is a 2-foot calcareous "vein" oblique to S_1 , strike 315° , $72^\circ N$. It exhibits slickensides and drag of the S_1 foliation. A grab sample yielded no gold. In thin section this rock consists of alternating parallel bands of fine grained calcite and plagioclase aggregates in nearly equal amounts, both carrying interstitial high magnesian chlorite that constitutes about 10% of the rock. The calcite bands contain lozenge-shaped ankeritic domains. Accessory minerals include apatite, zinc-rich chromite and abundant chromian titanomagnetite commonly displaying atoll textures, a feature of ultramafic rocks. Other indications of an ultramafic parentage are the high magnesian chlorite and a trace element analysis that includes 296 ppm Ni, an unusually high result in comparison to the nickel content found in the dozens of other rocks analyzed in the study for this field trip. We thus consider this "vein" to be a hydrothermally altered ultramafic dike. Gair and Thaden (1968, pl. 1) showed an outcrop of "hornblende lamprophyre" at the southernmost end of what was then the Highway 41 road cut. Their outcrop cannot be found today, but this dike may represent its eastward extension.

Marked on Figure 4 are five samples taken for whole rock major oxide and 32-element trace analysis. Two are from unfoliated pillow basalts, two are from the sheared lithologies, and the fifth is from the ultramafic dike. The whole rock results are shown on Figure 5.

Discussion

In this exposure chemically very similar rock units exhibit shearing that is preferentially developed in weaker units (zones of small pillows, lava interflow beds, more magnesian layers). Intervening more massive buttress units are resistant to shearing. The sense of shearing is nearly vertical.

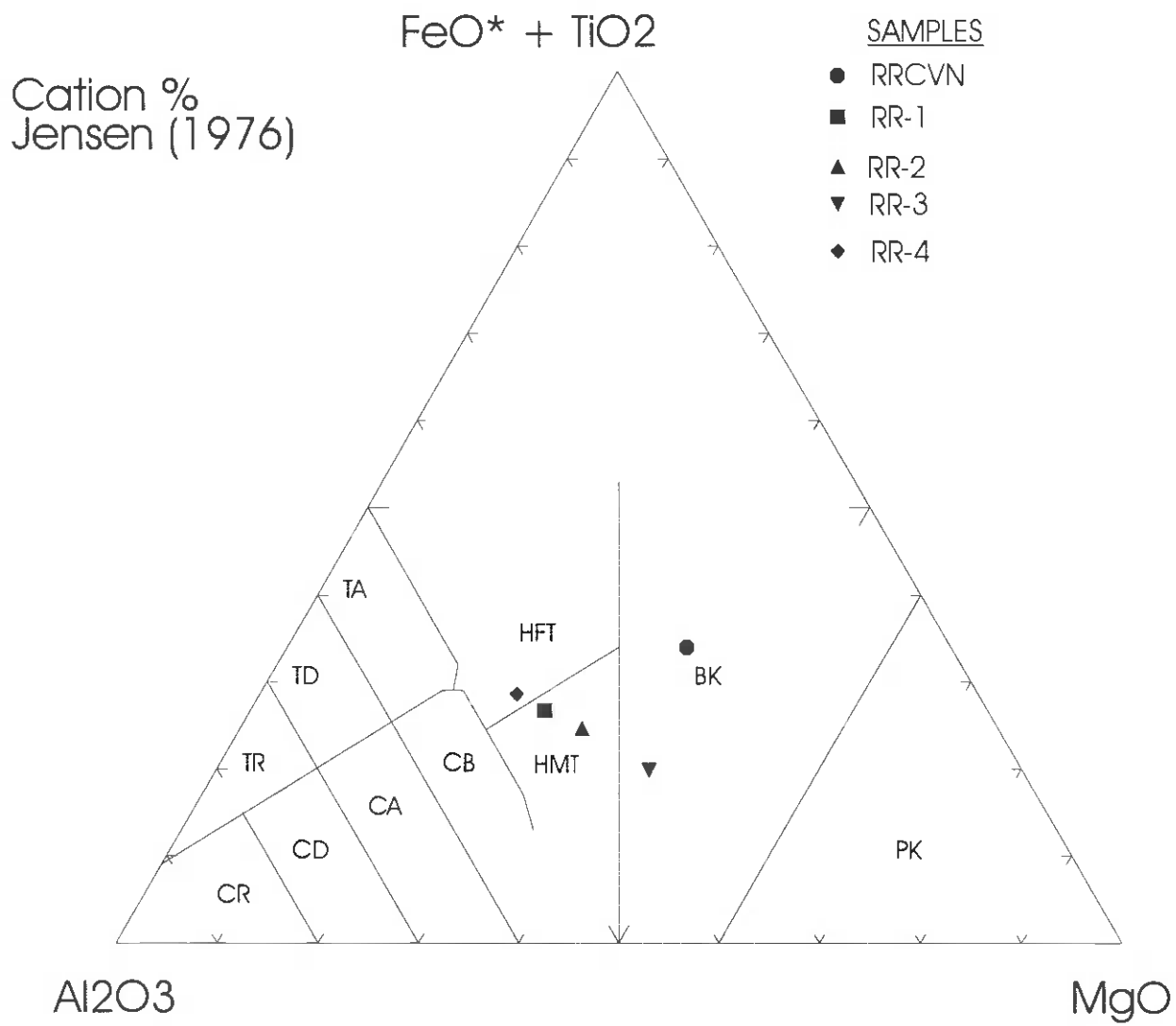


Figure 5: Stop SG-1

Gair and Thaden (1968) noted this outcrop on their map of the Marquette quadrangle, but didn't indicate shearing or slaty lithology here. A couple of miles to the southwest they did describe east-west shearing at the southern contact of the Mona greenstones and the overlying Proterozoic Enchantment Lake conglomerate. Mapping the next quadrangle west, Puffett (1974, p.43) recognized the Carp River Falls shear zone near that same contact and correlated it with the shearing in the Marquette quadrangle previously noted by Gair and Thaden. Both authors pointed out that the sense of shearing is strongly vertical. Puffett (1974) also recognized and named the Dead River shear zone and noted (p. 45), "The projection of the shear zone to the southeast across the Marquette quadrangle meets a conspicuous re-entrant in the shoreline of Lake Superior." Thus neither of these two major later-recognized block boundary shear zones is actually shown on Gair and Thaden's 1968 map. This was left to later authors of maps at various smaller scales, who usually place the Dead River shear zone as a west-northwest trend meeting the lakeshore at the approximate contact with the Mona formation basalt flow unit of the southern block and the Lighthouse Point basalt unit of the northern block of the Ishpeming Greenstone Belt. This would place the Dead River shear zone about $\frac{3}{4}$ mile due north of this field trip stop. (Figure 2) The zone seen here is a probable parallel, sympathetic structure.

Discussing the structural framework of the Ishpeming Greenstone Belt, Bornhorst and Johnson (1993, p. 4) stated, "The oldest recognized event (D_1) was recumbent folding. This was followed by upright folding about east-west oriented axes (D_2). Shear zones are interpreted to have formed during and later than D_2 and may have been reactivated during the early Proterozoic Penokean deformation." They went on to point out, "Rock units in all blocks are also cut by minor shear zones. These high-strain zones are characterized by rocks that are more intensely foliated than the surrounding rocks." We agree with these interpretations and offer the exposure at this stop as a case in point. Whether or not this particular shear zone is a major or minor one has yet to be determined. To the west it projects into an urbanized area with no outcrop.

The sheared lithologies at this locality exhibit varying levels of propylitic alteration (pyrite, carbonate, chlorite); significant trace amounts of gold can be found where pyrite and/or carbonate are well developed. As a practical matter, further exploration for gold in this shear zone is ruled out by its location.

Stop SG-2: Dead River Shear Zone with gold mineralization at Marquette Mall (Location map, Figure 2).

After parking at the head of the ski trail in the southeast corner of the Marquette Mall parking lot, walk about 500 feet ESE up the trail to an outcrop knob of undeformed metabasalt. This greenstone has an unusually high number of blocky hematitic fractures. The northern limit of this outcrop is a cliff face that is controlled by foliation planes striking 280° , 85° S. This cliff face represents the southern margin of shearing that was exposed in man-made outcrops in the bank of the Holiday Inn parking lot until it was recently covered by landscaping. R. Brozdowski (personal communication, 1988) reported anomalous gold values from Callahan's sampling of that sheared rock.

Returning about 400 feet westward down the trail, a makeshift wooden bridge crosses the stream leading to the motel's duck pond. Intermittently exposed along the stream are small outcrops of sheared chlorite-sericite rock with brown carbonate weathering rinds and oblique quartz veinlets. Some of this rock has small gray quartz phenocrysts, indicating a crystal tuff protolith. Of three widely spaced grab samples we took here, one gave .023 oz/ton Au, the other two were below MPC's detection limits. The sample that yielded the gold value was taken a couple of feet below the little wooden bridge.

Back at the Marquette Mall parking lot and moving west along its south bank, there is a 650 foot long exposure of highly sheared rock. Bornhorst and Johnson (1993, p. 9) gave a brief description of this outcrop: "... tuffaceous rock and a graphitic zone crop out."

This sheared phyllonitic rock is badly slumped northward towards the parking lot throughout much of its length. At its eastern end it is more hematitic than elsewhere, with reddish foliation planes resembling the fractures in the relatively underformed greenstone to the east. Throughout its entirety there is a strong presence of chlorite and sporadic sericite on foliation planes, with much of the rock exhibiting a maroon-reddish color due to weathering of chlorite and ferroan carbonate. Where not slumped, foliation measurements cluster closely about 280° , vertical.

There are some zones of chlorite-poor rock with small quartz eyes indicating a probable tuff protolith, similar to that found in the stream to the east. Near the eastern end of the outcrop is an irregular foliation-parallel two inches to 2 feet layer of nearly pure graphite. Our grab sample of the graphite gave no Au. One or two feet across foliation from the graphite is a thin semi-parallel layer of rusty to black gossan with selvages of massive and semi-massive pyrite carbonate breccia. From the pyrite-gossan zone, Gleason (1986) reported values up to 2 gm/tonne (.06 oz/ton) Au. Our grab sample of the gossan gave .037 oz/ton Au, while our sample of pyrite breccia selvages gave .028 oz/ton Au. A polished thin section sample of the pyrite breccia shows that there are two generations of pyrite in a quartz-calcite-chlorite

gangue, with the calcite late in the paragenetic sequence. The first generation pyrite is large and often framboidal, corroded and partially replaced by quartz and second generation pyrite in smaller, euhedral crystals. Heavy traces of covellite (CuS) occur as inclusions in the second generation pyrite and as tiny free grains in the gangue. Other inclusions within pyrite found by the microprobe include chalcopyrite and sphalerite as lesser trace sulfides. Accessory minerals found in this breccia are monazite and ilmenite partially altered to rutile, a common result of hydrothermal alteration. No grains of free gold were found in this thin section sample. Besides the highly anomalous gold in the corresponding assay grab sample, the following anomalous trace elements were present (ppm): Ag-3; As-252; Cu-1700; Pb-68; Zn-124; U-10.

About 150 feet from the western end of this exposure is a 2-foot complexly brecciated chlorite-calcite-quartz-graphite vein with strong vertical hematitic slickensides and minor copper stain. The slickensided hangingwall of this vein strikes, $290^{\circ} 75^{\circ}\text{N}$. Our grab sample yielded .005 oz/ton Au, as well as 244 ppm Cu and 100 ppm Zn. Study of a corresponding polished thin section did not find any gold grains but confirmed the presence of very fine grained chalcopyrite and covellite in irregular trains following late fractures and rimming graphite. This vein appears to be cut off by a northerly cross fault. About 75 feet from the western end of the exposure is a thin discontinuous vein of similar composition; our grab sample yielded no Au.

About 100 yards southward and uphill from the west end off the Mall exposure is a slumped-in and partially flooded small open cut next to the north-flowing creek. In the south wall of this old mine pit there is an exposed patch of rusty weathering, ankeritic phyllonite similar to the Mall exposure lithology. There are no dumps or other present evidence of the ore mined. This is the Eureka mine (Williams, 1890). Gair and Thaden (1968, p. 69) provided the following: "The principal occurrence of iron in the Marquette-Sands area was at the old Eureka mine ... Perhaps as much as several hundred tons of earthy goethitic iron ore was mined from a shear zone about 5 feet wide in chloritic slaty greenstone (Mona Schist). Secondary quartz and iron-bearing carbonate were deposited along the shear zone in places, prior to formation of the iron ore. The ore resulted from oxidation of carbonate and chlorite, the concentration of iron, and the removal of silica, MgO, CaO and alumina by ground water circulating along the shear zone. Virtually all mining was done prior to 1880, and whatever ore was extracted was shipped to local charcoal-burning smelters. There were several unsuccessful attempts to renew mining in the 1880's and three test holes were drilled at the site in the 1920's".

Discussion

This locality was last mapped by Gair and Thaden (1968, Pl. 1). Their map shows only a couple of small exposures here, marking the contact between their Lower and Lighthouse Point members of the Mona Schist. We believe that the outcrops here represent the southern margin of the Dead River shear zone. The presence of gold and base metals in the Mall exposure is direct evidence of their localization by major shear zones, and we suspect that some of the ore produced by the Eureka mine may have been, in part, gossan after sulfides.

The trend of shearing projects from here westward along the valley of an E-W creek. No exposures could be found along it except a few outcrops of a narrow E-W magnetic diabase dike on its south side 4,200 feet west of here, probably emplaced at or close to the southern margin of the shear zone. That diabase is not on any published map.

Stop SG-3: Keweenaw diabase in hornfelsed, foliated Archean metavolcanics (Location map, Figure 2).

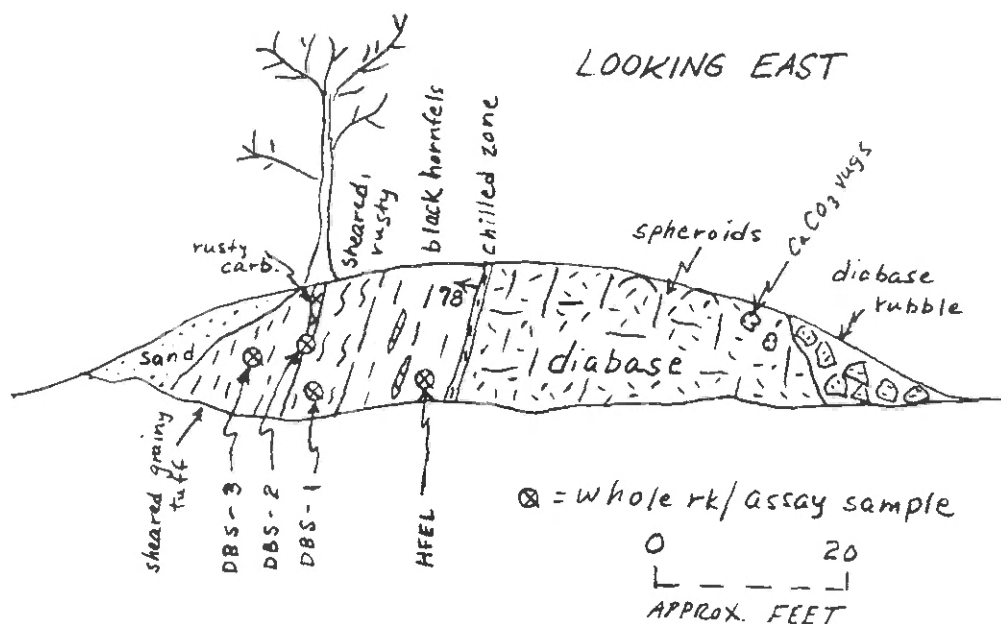


Figure 6. Sketch cross section of outcrop at Stop SG-3, looking east.

This outcrop was last mapped by Gair and Thaden (1968, Pl. 1) as Late Precambrian diabase with a small adjoining patch of "felsite" belonging to their lower unit of the Lighthouse Point Member of the Mona Schist. There is no outcrop description in their text. This one is part of a series of outcrops of a long narrow diabase dike that Gair and Thaden traced eastward into Lake Superior at Lighthouse Point. Here it strikes 250°, dip 80°N. It appears to be about 50 feet thick, although its southern contact is not exposed. The diabase is non-foliated and is magnetic throughout.

Figure 6 is a sketch cross section of this exposure. At the south end the diabase is medium grained, has a felty texture and contains rare vugs lined with drusy calcite. It shows rectangular jointing that controls incipient spheroidal weathering at the erosion surface; the joint planes are hematitic and calcareous. The diabase grain size lessens northward to a fine grained but still magnetic chilled margin at the host rock contact. This contact is strongly foliated parallel to the dike margin for a few inches. Beyond that the immediate host rock is a black, non-magnetic, aphanitic hornfels with strong foliation defined mostly by prominent pink K-spar-quartz laminae. This rock carries a trace of disseminated extremely fine-grained pyrite, and some discontinuous foliation-parallel lenses of coarsely crystallized quartz. It weathers light greenish gray. Outward to the north, the host rock becomes rusty weathering, slaty and less "baked"-looking, all the while exhibiting strong foliation planes closely clustered around 280°, 80°N. The source of the rusty color appears to be numerous foliation partings of ferroan carbonate; no pyrite is visible on a fresh surface. An irregular 4-6 inch foliation-parallel quartz-iron oxide vein marks the transition northward to non-thermally altered grainy-light greenish-gray sheared rock with rusty foliation planes at 275°, 85°N continuing to the northern limit of the exposure.

Four grab samples of the host rock are shown on the sketch cross section. Two of these were clearly below MPC's detection limit for gold (samples DBS-2 and 3). The other two returned values at or near the detection limit and were re-analyzed by Chemex using FA-AA, returning weakly anomalous gold values: DBS-1, 51 ppb; HFEL, 33 ppb. No unusual trace element signatures were present in any of these samples.

Study of a polished thin section of a sample corresponding to assay sample HFEL confirmed that the pink bands consist of quartz phenocrysts in a K-spar groundmass. The darker-colored domains of this rock have a porphyritic texture with scattered phenocrysts/crystals of albite-oligoclase, quartz (often in biminerallitic grains with pyrite), and composite large grains or fragments of quartz-plagioclase. The dark color appears to be mainly due to biotization of numerous foliation-defining chlorite-quartz-plagioclase laminae and to an overall content of about 5% opaques: pyrite and ilmenite altered partially to rutile. The nature of the coarse grained components suggests that this rock was originally a crystal lithic tuff. The

thermal metamorphic effects near the contact of the diabase dike appear to be limited to prograde alteration of chlorite to biotite and recrystallization of quartz and feldspar. Figure 7 is a Jensen cation plot of the whole rock analyses of the four samples taken at this stop.

Discussion

The foliation in the weakly hornfelsed country rock here is at an oblique angle to the diabase dike, (which can best be seen at the top of the outcrop knob). Because of this, we believe this foliation pre-existed the emplacement of the dike. We also believe that much of the foliation in the host rock here is the result of shearing, and that this outcrop lies near the middle of the Dead River shear zone. The southern boundary of this shear zone would lie near the Marquette Mall outcrop at Stop SG-2. The emplacement of this diabase dike within such a large zone of weakness would not be unexpected.

Gair and Thaden (1968), though noting shearing in their text from place to place in the Archean rocks of the Marquette Quadrangle, did not emphasize its importance, nor illustrate it on their map. They also found very few outcrops of their lower unit of the Lighthouse Point Member, most of which are shown as "felsite". About 1200 feet NNW of here, their map shows a cluster of 4 small outcrops on a low hill, marked as "felsite". The Westwood Mall and its parking lots now cover them, but we suspect that these outcrops would have exhibited shearing similar to here. About 500 feet further north in the woods behind the Mall, a new east-west street and sewer line were being constructed in the fall of 1998. The construction equipment tore up the tops of several small subcrops of sheared rock whose composition varies from highly chloritic to nearly pure massive sericite. It was not possible to obtain dips, but the strike of the shearing is east-west. These exposures lie near the probable northern contact of the Dead River shear zone. Since it's unlikely that they'll be still available in the spring of 1999, we offer Stop SG-4 as an alternative.

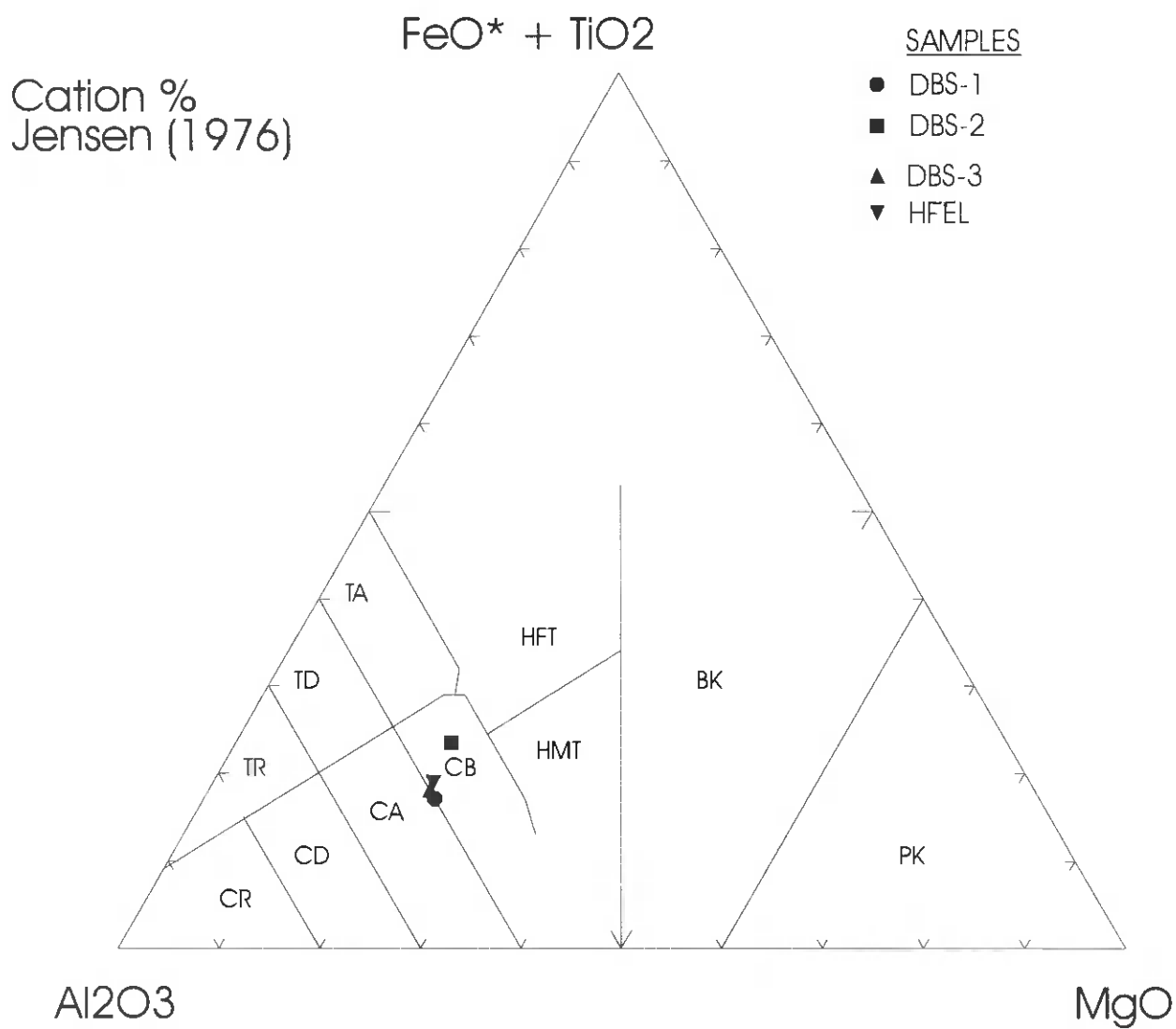


Figure 7: Stop SG-3

Stop SG-4: Northern margin of Dead River Shear Zone on Wright Street (Location map, Figure 2).

This is an optional stop that is included here for those interested in seeing more of the Dead River Shear Zone in the Marquette area. This exposure is very close to a busy highway, and care should be exercised when visiting it. About 65 feet of sheared greenstone is exposed here on the east side of Wright Street. The lower level of the exposure was recently created by widening the road, and was not available to Gair and Thaden (1968), who showed the upper part of the exposure as a lithology labeled “interlayered massive basalt(?)” on their map (Pl. 1).

The degree of shearing is variable here, but much of it is intense. Foliation becomes generally more strongly developed from north to south, and strikes E-W, nearly vertical. In the small cut above the lower ledge, curvilinear sheared forms similar to the sheared pillows at Stop SG-1 are present. Figure 8 is a photograph of pencil cleavage developed further south as shearing intensifies. There is weak carbonate alteration in some of the most heavily sheared rock, but it is not pyritic; we didn’t sample for gold here.



Figure 8. Looking due east at pencil cleavage developed by shearing in greenstone in low roadcut, east side of Wright Street, Stop SG-4.

The northern part of this outcrop consists of nearly chaotic chloritic foliation that appears to result from the contact with a shear-resistant dike of non-magnetic gabbro that is only weakly foliated. Only a couple of feet of this gabbro are exposed in the roadcut, but a larger, glacially smoothed outcrop of it lies above and a few yards east of here.

Discussion

About 400 feet to the north, on the east side of the road is an outcrop of relatively undeformed metabasalt; glacially polished outcrops of similar rock are exposed in the south side of the gravel pit being converted to a housing development a couple of hundred yards further ENE. These rocks appear to be Lighthouse Point basalt typical of this area (Johnson and Bornhorst, 1991). So we would place the northern boundary of the Dead River Shear Zone, if not at this outcrop, then no more than a few hundred feet north of here. Figure 2 shows what we think are the approximate limits of the shear zone, which corresponds roughly to the lower unit of the Lighthouse Point Member of the Mona Schist of Gair and Thaden (1968), in turn corresponding roughly to the "Eureka Group" of Williams (1890), nomenclature that was discarded by Van Hise and Bayley (1897). This would make the Dead River Shear Zone 3,000 feet wide at this point. Puffett (1974, p. 44) noted that the Dead River Shear Zone four miles west-northwest of here is about 3,400 feet wide.

To better define and understand the Dead River Shear Zone in this important hinge area between the northern and southern blocks of the Ishpeming Greenstone Belt, re-mapping and structural study of existing and newly created outcrops are needed, before it's too late. The ex-urban growth around Marquette, although presently creating new outcrops, will eventually result in a net loss of exposures.

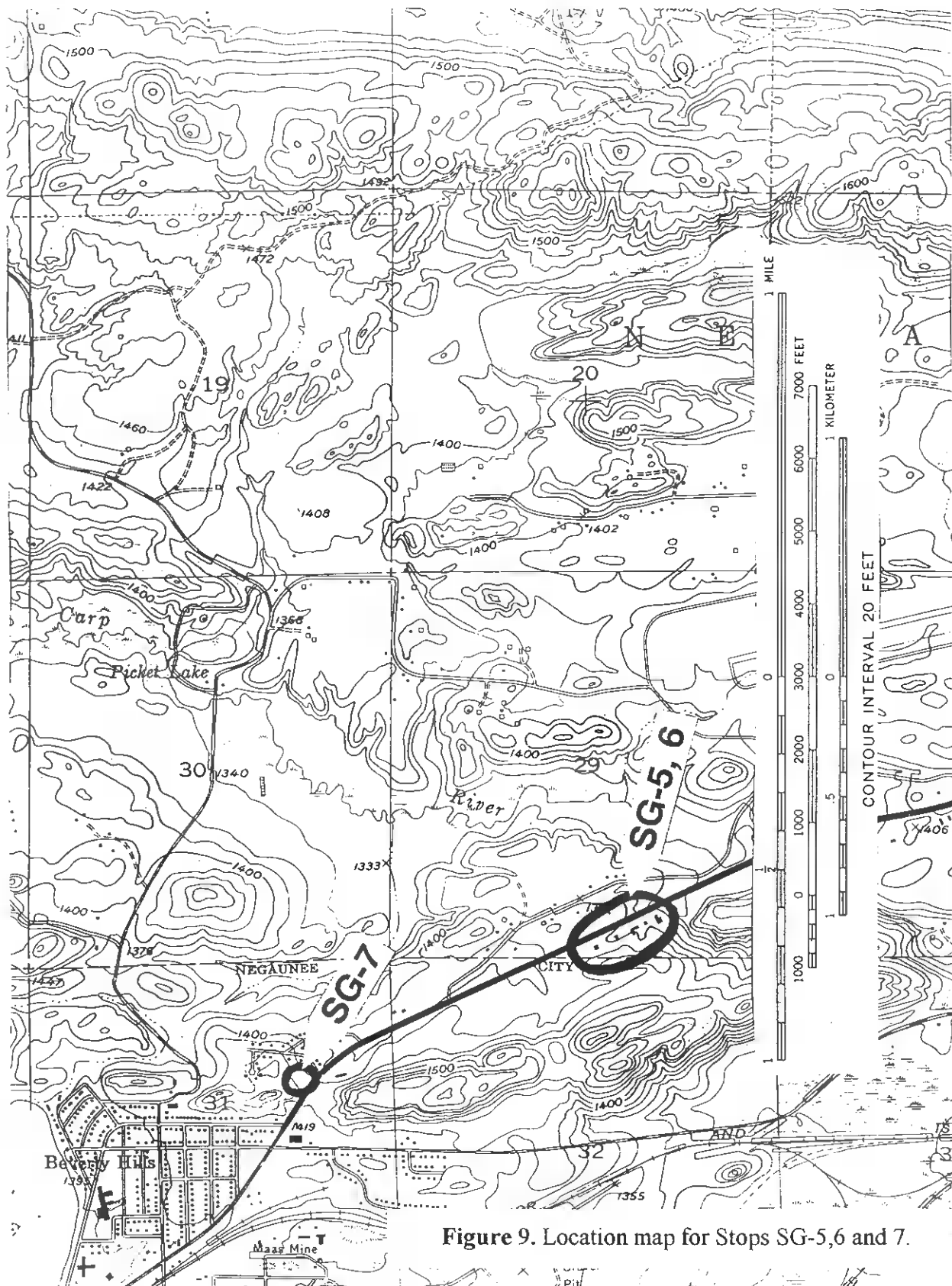


Figure 9. Location map for Stops SG-5,6 and 7.

Stop SG-5: Progressively sheared/altered metavolcanics in Carp River Falls Shear Zone.
(Location map, Figure 9).

Puffett (1974) last mapped this locality as "undifferentiated greenstone" within the Carp River Falls shear zone. Dealing with this exposure specifically, he included a photograph of its most sheared and altered part, and described it as follows (p. 43): "Sericite, chlorite, carbonate, and leucoxene are the most conspicuous alteration products. Weathered surfaces are commonly stained brown from oxidized iron minerals. Quartz-carbonate veinlets form an anastomosing network in some rock. Copper minerals are present locally. Analytical data suggest that the altered rocks are enriched in CaO and Co₂ (Table 12)."

Puffett's analysis from here gave an anomalous copper value, 90 ppm. W.A. Bodwell (personal communication, 1998) reports having noted trace chalcopyrite and copper staining here, but they are not easily found.

This exposure was a 1988 I.L.S.G. field trip stop described, in part, as follows (Bornhorst and others, 1988): "The rocks in this roadcut have a well developed close-spaced foliation (N75-88W, 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."

Bornhorst and others (1988) also pointed out that near the very eastern end of the outcrop are probable relict pillow rinds. As seen elsewhere on this field trip, these are gradually obliterated by shearing as one moves westward along the outcrop. The chloritic sheared metabasalt gives way progressively to more and more rusty weathering carbonate-sericite altered rock; we believe it represents a progressive change from propylitic alteration to weak potassic alteration in a rock of the same parentage.

In the lighter colored carbonate-sericite altered rock near the western end there is a 6-inch pyritic carbonate zone. Our grab sample of this gave .005 oz/ton Au (sample STOP 3). A 70-foot chip sample across the entire sericite-carbonate altered zone here (not including the pyritic grab sample) gave undetectable Au (sample STOP-3A). An FA-AA re-analysis by Chemex of the pyritic grab sample gave a value of 90 ppb Au, confirming MPC's results. We also took whole rock samples from the very eastern end of the exposure in the pillowed greenstone (sample 5-1), one from moderately sheared rock near the middle (5-1), and one at the western end of the outcrop in approximately the same spot sampled and photographed by Puffett (our sample 5-3). Whole rock analyses were also done on the two samples taken for gold assay; sample STOP-3A is the most representative of the light colored sheared rock at the western end of the exposure, since it was a composite chip sample across 70 feet of it. Figure 10 is a

Jensen plot showing the results. (Note that sample STOP 3 is anomalously high in iron because it was chosen for best pyrite content).

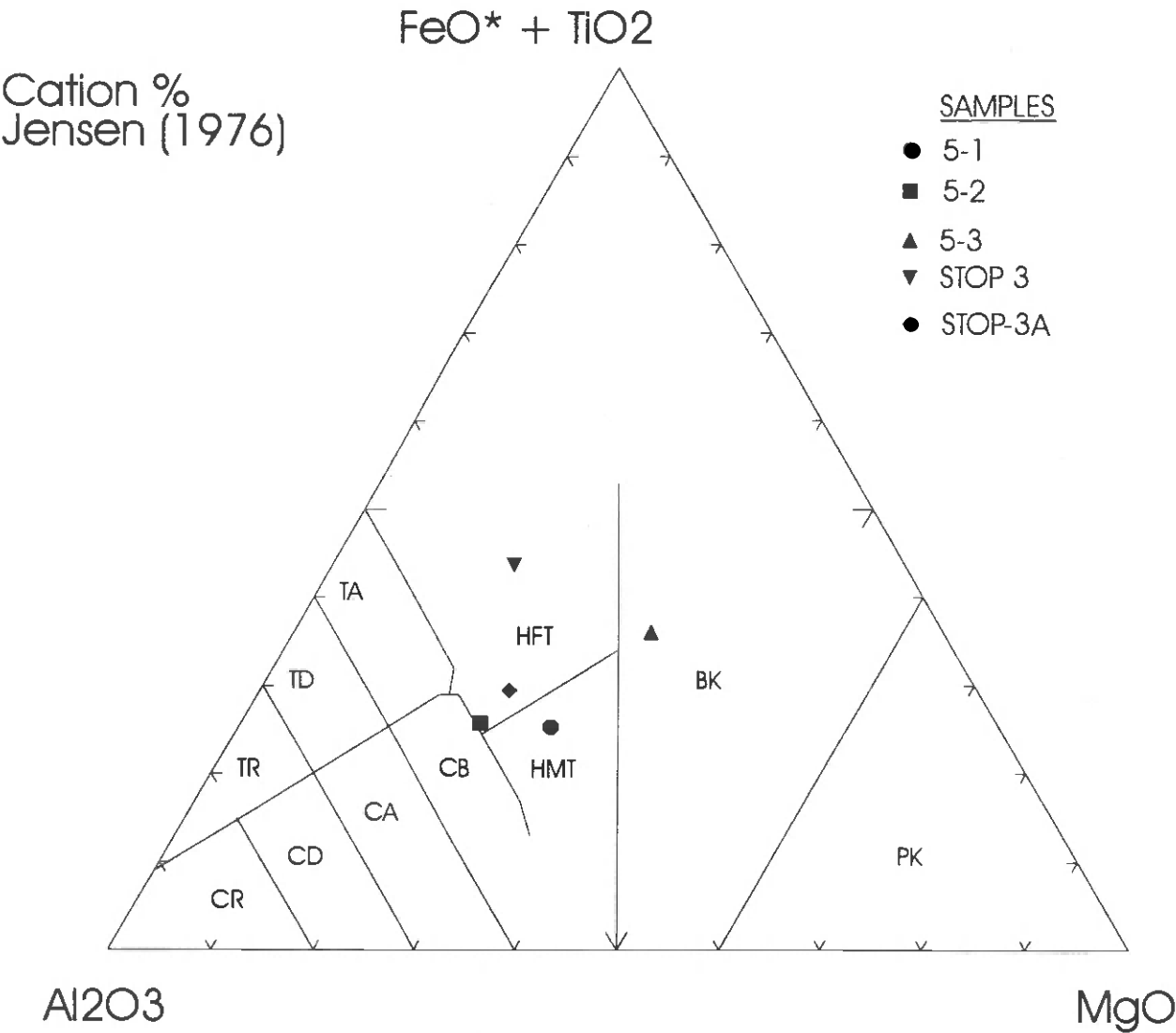


Figure 10: Stop SG-5

A polished thin section was made of a specimen corresponding to pyritic grab sample STOP 3 that yielded anomalous gold. Megascopically this specimen is a chlorite-sericite schist hosting a foliation-conformable ½-inch veinlet of carbonate. Under the microscope and electron microprobe the host rock is a fine grained mixture of 50% quartz, 30% chlorite and 20% muscovite/sericite, containing about 1% tiny grains of disseminated chalcopyrite, as well as trace amounts of tiny disseminated rutile grains. The carbonate veinlet is a mosaic of coarse grains of zoned dolomite with high-manganese cores, with about 10% interstitial high-iron chlorite. This vein assemblage hosts schlieren texturally similar to the host rock except that these fragments have no quartz, consist primarily of zoned ankerite with dolomitic cores and contain about 25% opaques, mostly Mn and Fe oxides, but also abundant fine grained euhedral pyrite and subordinate chalcopyrite. One of the chalcopyrite grains was found to have inclusions of non-argentiferous tetrahedrite and one 3-micron grain of high-gold electrum (photo, Figure 11). This was the only gold grain found in this sample. Arsenopyrite was not found, but trace element analysis of the corresponding assay sample yielded 170 ppm As.

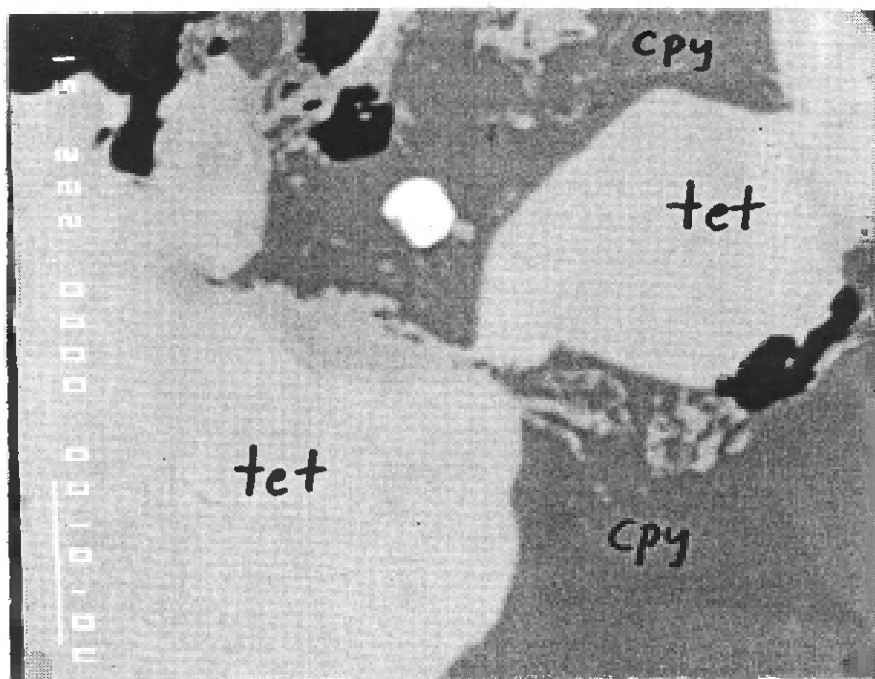


Figure 11. Polaroid photo of backscattered electron detector image, sample STOP 3. White vertical scale bar at lower left is 10 microns. Bright 3-micron grain of high gold electrum in chalcopyrite (cpy) that also contains larger inclusions of tetrahedrite (tet). Black areas are gangue.

Discussion

Puffett (1974, p. 43-44) noted copper minerals at more than one locality in the Carp River Falls shear zone, an encouraging base metal association from the gold exploration point of view, since gold occurs directly with a copper mineral here. This outcrop is close to the north margin of the shear zone. The south margin appears to be marked by bluffs that are controlled by E-W foliated greenstone, across the highway behind Ball Moving and Storage, making the zone about 400 feet wide at this point, mostly covered by U.S. Highway 41. We will cross the highway here to see more evidence of gold mineralization.

Stop SG-6: Gold-bearing glacial erratic (Bill Bodwell's Boulder) . Location map, Figure 9.

This was first noticed and sampled by Bill Bodwell in the 1980's. His attempts to find a bedrock source in the immediate vicinity were unsuccessful. However, judging by its large size and angularity, this boulder hasn't traveled very far. The eastern end of the boulder shows the preserved remains of an original bedrock surface.

This rectangular 5 by 10 foot block was unearthed in sandy glacio-fluvial sediments during site clearing for the moving and storage facilities, and has lain in its present position for about 30 years. It consists of about 50% close-spaced, sub-parallel *en echelon* white quartz veins up to one foot thick. The veins contain 10%-20% light brown weathering ferroan carbonate in blobs and seamlets, lesser small masses of dark green euhedral chlorite, and rare small blobs of very late stage black tourmaline. Interstitial to the quartz veins, the other 50% of the boulder is made up of highly foliated "horses" of carbonate-altered chloritic greenstone, showing an impressive internal continuity of foliation throughout the boulder. The style of veining is "ladder veining", consistent with oblique tensional development in a sheared rock.

The quartz veins contain patchy blobs of pyrite with lesser chalcopyrite, and abundant malachite staining. Bill Bodwell's initial grab sample of the sulfide-bearing quartz gave .267 oz/ton Au; two later samples yielded .036 oz/ton and .006 oz/ton, respectively. All of these samples yielded +10,000 ppm Cu, showing that copper, although obviously mineralogically associated with gold here, does not necessarily have a direct assay correlation (Bodwell, 1988, written communication). Our grab sample of the quartz-sulfide gave .006 oz/ton Au. Our sample of the barren-looking host greenstone yielded .005 oz/ton Au.

This wide range of gold assay results demonstrates the “nuggety” distribution of gold within this boulder, a phenomenon that requires special assaying techniques to obtain a representative value.

However, the main point of this field trip stop is that this boulder likely came either from the Carp River Falls shear zone or from a similar zone nearby. It’s interesting to note that glacial striae on the pillowed greenstone near the USGS benchmark at the eastern end of the Stop SG-5 outcrop across the highway are nearly east-west, paralleling the shear zone. The strongest inference from the evidence at both this stop and the preceding one is that the Carp River Falls shear zone is in itself a gold exploration target.

Stop SG-7: Basal Proterozoic Enchantment Lake conglomerate in contact with Carp River Falls shear zone in Archean metabasalt. (Location map, Figure 9).

This spot has been a classic field trip stop for seeing the features of the Mesnard and Ajibik quartzites in the U.S. 41 roadcut. But our interest lies further down-section in the Proterozoic, at its contact with the Archean. This locality was last mapped by Puffett (1974), who showed the Archean rocks here as Mona Schist, now included in the informal lower basalt flow unit of the Mona Formation of Bornhorst and Johnson (1993). Puffett’s map (Pl. 1) shows the Carp River Falls shear zone as a line passing about a half mile north of here, but he stated in his text (p.43), “The zone is indicated on the map as a narrow, well defined structure, but the symbol marks only the north limit of a broad zone of sheared and altered lower Precambrian rocks.”

After parking at the intersection of U.S. 41 and Chippewa Drive, walk about 100 feet northwest past the billboard to a series of low outcrops in the woods. The first one encountered is glacially polished, and exposes the Carp River Falls shear zone in contact with the overlying basal conglomerate of the Enchantment Lake Formation. Both east and west of here there are numerous nearby exposures of the shear zone lying north of this contact. A width of about 200 feet of the shear zone is exposed in the immediate vicinity. Shearing intensity is variable; relict pillow textures are present in exposures about 150 yards to the east. Here at this exposure, the Archean greenstone shows strong foliation striking 280°, 85° S. A parallel foliation also affects the lowermost part of the overlying conglomerate.

The conglomerate is about 5 feet thick, but is somewhat patchy and discontinuous, grading intermittently both upwards and laterally into coarse grained quartzite containing only occasional small

cobbles or pebbles. The entire unit, including the quartzite, is 20-50 feet thick, forming an erosionally resistant E-W ledge. South of it, a 100-foot-wide low swale occupies the interval presumed to represent erosionally recessive sericite slate that constitutes the upper part of the Enchantment Lake Formation in this area (Puffett, 1974); the very uppermost part of this lithology can be seen below the Mesnard quartzite back at the highway.

The basal conglomerate can be traced westward from here at the initial outcrop for about 250 feet. The coarsest layers of it consist of +80% white vein quartz cobbles. It bears a striking physical resemblance to the low-pyrite varieties of the Witwatersrand conglomerate of South Africa, and occurs in a similar geologic setting. We took three grab samples of conglomerate from these outcrops. Two of them returned detectable gold: .003 oz/ton and .005 oz/ton. These two were re-analyzed by Chemex and returned 65 ppb and 37 ppb Au, respectively. These results suggest a problem with nugget effect at the low end of the detectability scale, which would not be surprising in the case of placer gold. No sulfides are megascopically visible in this rock, nor were any found under the binocular microscope in an examination of the crushed rejects from our grab samples. We have not done any further testing to determine the internal domains hosting these low but anomalous gold values.

Discussion

Although it may turn out that the traces of gold in this rock are caused solely by the foliation event that affects it, a paleoplacer origin seems to us to be much more likely. For economic concentrations of paleoplacer gold to be found in the Enchantment Lake conglomerate, the first consideration would be whether or not gold deposits in the Archean terrane were actually in existence prior to the erosional events that led to the deposition of the conglomerate. The only known significant gold mineralization in Proterozoic rocks in this region occurs in veins at the Champion iron mine; the Proterozoic is otherwise notable for its paucity of gold showings. Bornhorst and others (1998) have attempted to constrain the dates for some of the mineralization in the Archean rocks by lead isotope studies, obtaining a model age of 2,455 to 2,510 Ma for galena that occurs with gold in the Ropes mine, but also mentioning structural evidence suggesting that the Ropes gold was deposited at about 2,690 Ma. They also pointed out that ages are poorly constrained for the timing of the rifting that initiated the earliest Marquette Range Supergroup sedimentation that this conglomerate represents.

Whatever the absolute age(s) of the gold-bearing veins in the Archean rocks of the Ishpeming greenstone belt, this conglomerate probably post-dates them. Evidence for this is the high preponderance

of vein quartz within it at this locality, the presence of anomalous gold in it , and its apparently unconformable relationship with the Carp River Falls shear zone, which was demonstrated to be gold-mineralized at Stop SG-5 of this field trip. Whether or not a paleoplacer-type gold deposit within this unit is a prime target for exploration is another matter. There are very few exposures of the Enchantment Lake Formation, and especially few of this thin conglomeratic phase. The many samples needed for assaying , provenance studies and the like would nearly all have to be obtained by expensive subsurface means over a wide area.

Stop SG-8: Lithology-selective ductile shearing with boudinage in the Carp River Falls shear zone. (Location map, Figure 12).

This locality was last mapped by Cannon and Klasner (1977), shown as part of their Precambrian W mafic-ultramafic complex. The revised stratigraphy of the Archean rocks of the Ishpeming greenstone belt (Bornhorst and Johnson, 1993) assigns it to the informal basalt flow unit of the Kitchi Formation. Beginning about 1/8 mile east of here, Cannon and Klasner mapped a large area of Precambrian W serpentinite, now considered part of the Deer Lake peridotite. About 1/4 mile to the northeast are a number of outcrops of a very fresh looking, nearly unfoliated biotite tonalite intrusion that we informally refer to as the “Mockler tonalite”, named for an adjacent small gold prospect; Cannon and Klasner mapped that outcrop area as Precambrian W felsic rocks. Only a few hundred feet south of here Cannon and Klasner’s map shows a fault contact between the Archean and the Proterozoic. Bornhorst and Johnson (1993) included this in the Carp River falls shear zone.

This exposure was not available to previous workers. It was created only very recently, when the Marquette County Road Commission straightened the approach to the railway underpass immediately south of us. The Road Commission dumped a very large pile of excess blasted rock from this new roadcut in a gravel pit that lies a couple of hundred yards southeast.

Figure 13 is a detailed map of this exposure. It shows a wide variety of rock types, which are affected by an east-west zone of ductile shearing that varies from weakly to intensely developed, depending on the rock type. There is evidence here for multiple deformation: a nearly horizontal S_2 crenulation cleavage is superimposed on a vertical S_1 cleavage, and is mimicked at all scales by near-horizontal boudins of foliation-resistant veins and rock units (see photo, Figure 15).

Figure 12. Location map for Stops SG-8, 9 and 10.

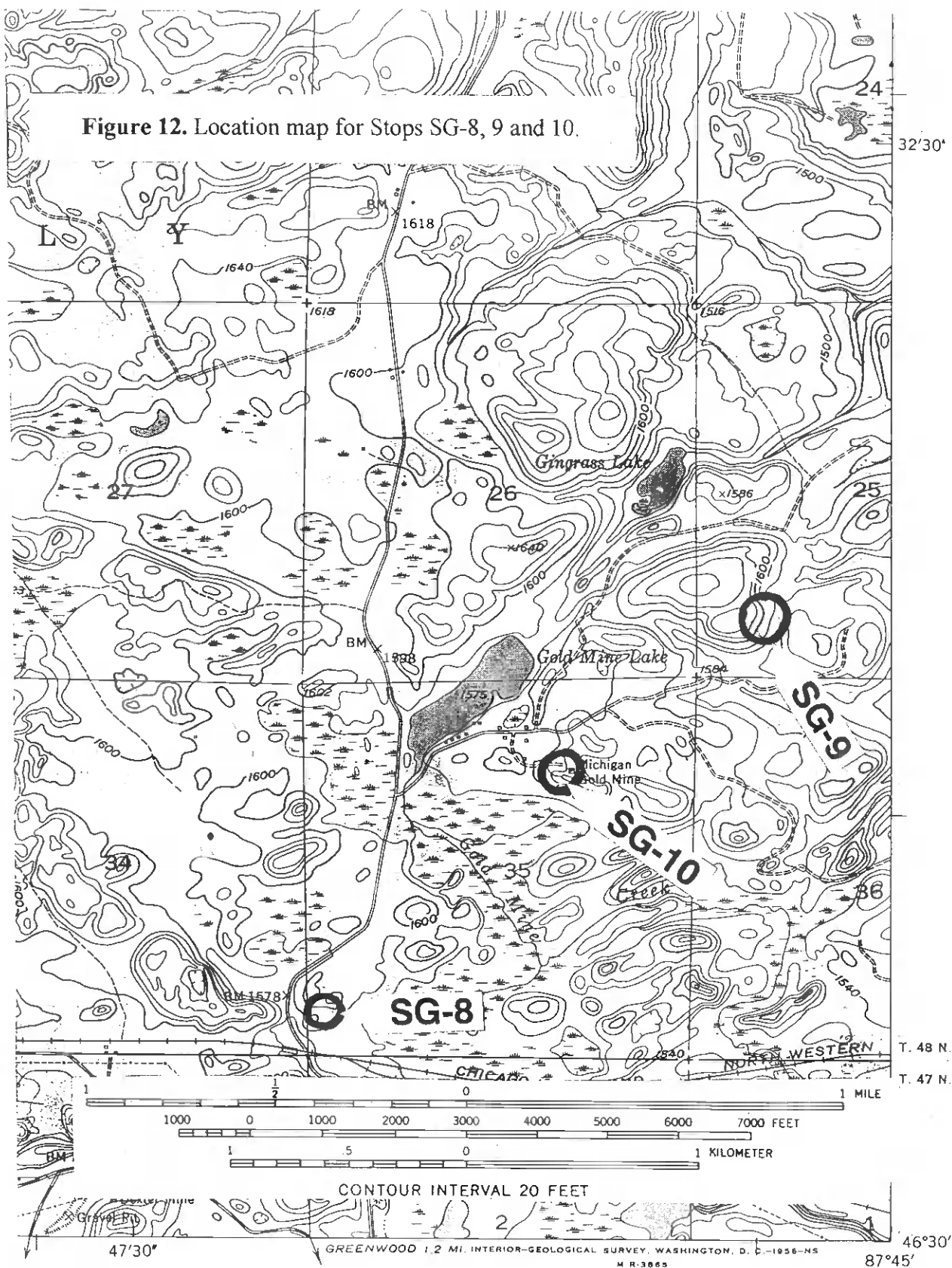
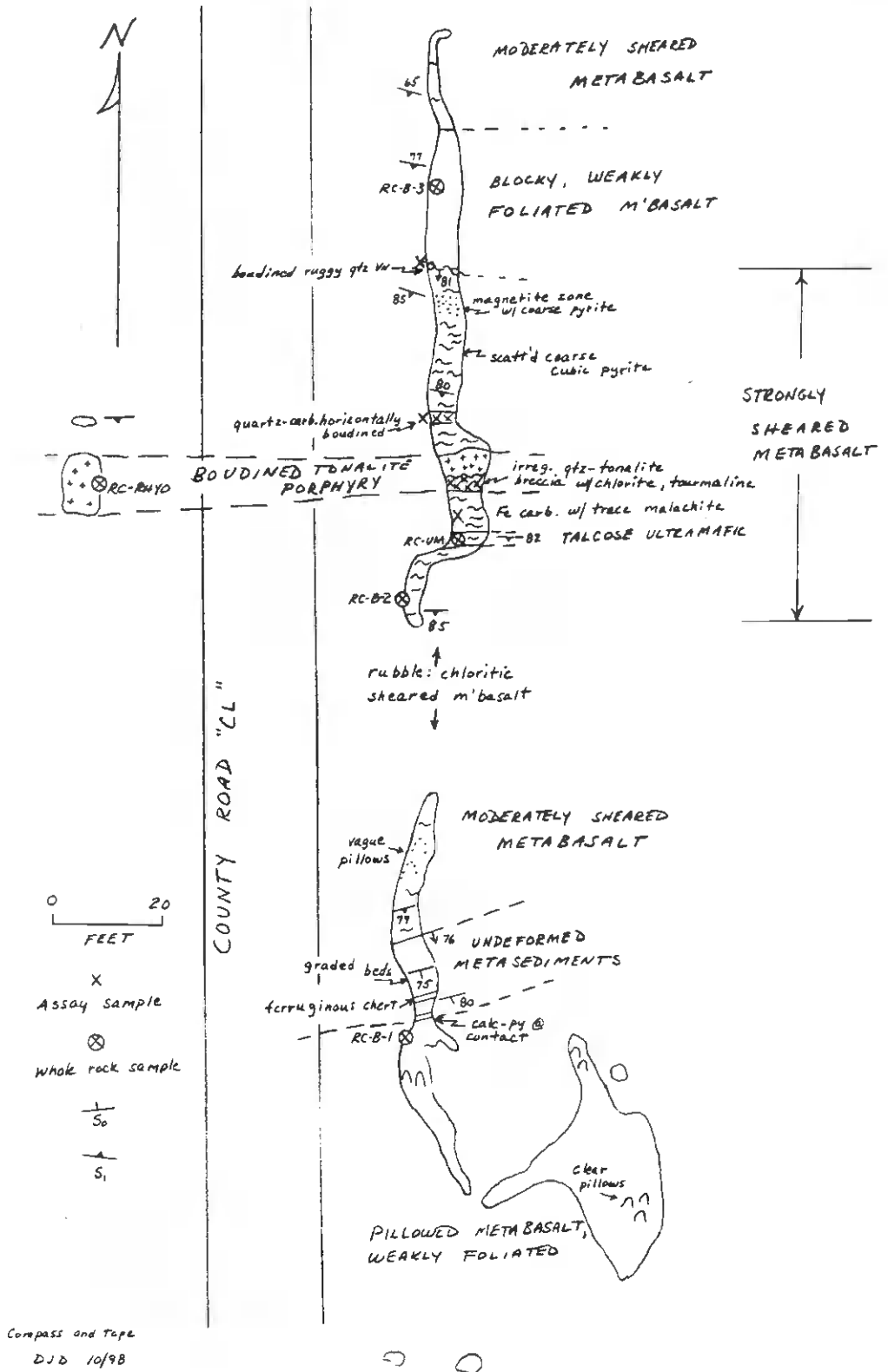


Figure 13. Plan map of Marquette County Highway "CL" roadcut, Stop SG-8.



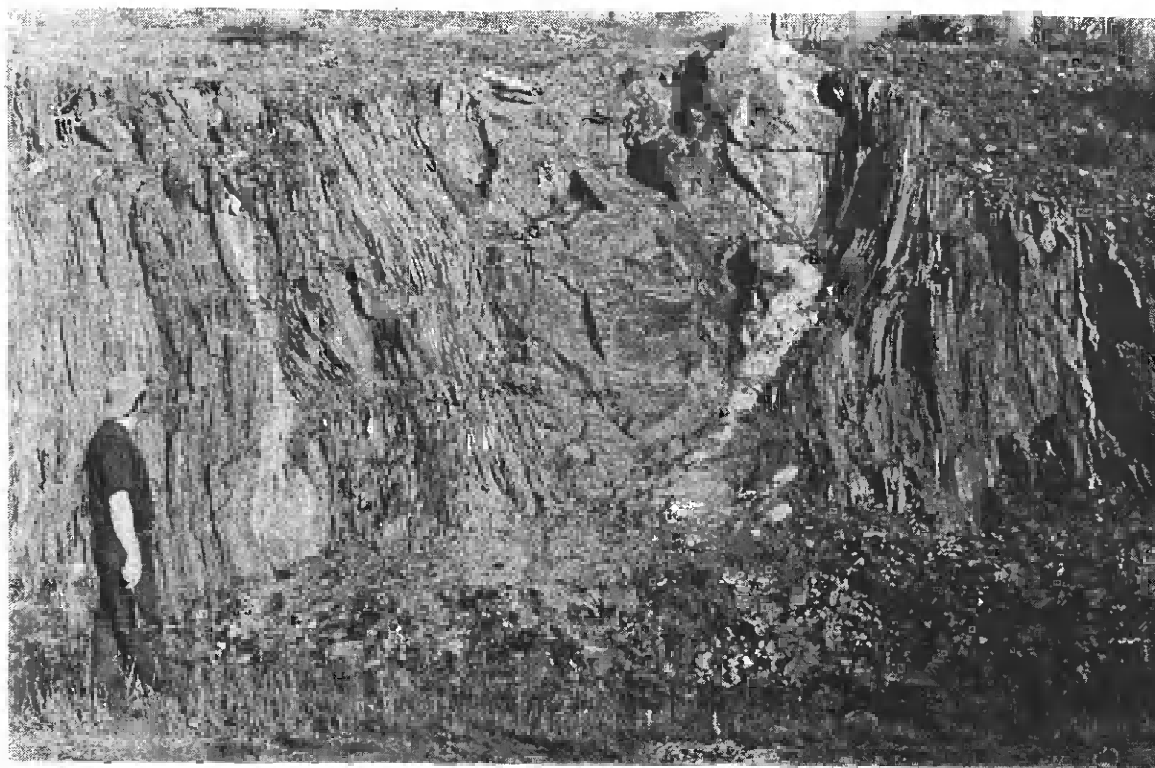


Figure 15. Looking eastward at roadcut exposure, Stop SG-8. Near center of photo is mega-boudined blocky tonalite porphyry with brecciated south margin of tonalite fragments, quartz, chlorite and tourmaline. Tonalite mega-boudin is enveloped in highly sheared basalt that also hosts horizontally boudined quartz-carbonate vein near left side of photo. Highly sheared talcose ultramafic is at far right.

This exposure exhibits lithologic and structural features too numerous to be described in detail in this paper; the highlights will be briefly mentioned. Near the south end, a 15-foot layer of virtually undeformed graywacke and minor pink chert lies between weakly foliated pillowed metabasalt and moderately sheared metabasalt. The graywacke has graded bedding, but tops are not clear. The southern contact of the sediments with the basalt appears to be conformable, but the northern contact with the moderately sheared basalt is marked by pyritic slickensides. Moving northward past a rubbly interval of near-outcropping sheared basalt, shearing becomes progressively more intense, and seems to be centered on a 4-foot zone of talcose, papery-thin sheared ultramafic rock. Although none can be found at the outcrop itself, a piece of this rock found in the gravel pit waste pile contained cross-fiber chrysotile. On the Jensen cation plot of our whole rock analyses from this exposure, the sample from this talcose material

plots in the peridotitic komatiite field (see Figure 14). This rock is either an apophysis of the Deer Lake peridotite, or a tectonically emplaced slice of it; it exhibits vertical rodding but horizontal slickensides.

Because of the structural deformation here, it's problematic whether the boudined tonalite porphyry is a dike or a sill. This is a fine grained dark pinkish gray rock with up to about 20% small feldspar phenocrysts, which in thin section are all highly sericitized albite-oligoclase. The groundmass composition is: a few percent opaques, (about $\frac{3}{4}$ rutile pseudomorphing ilmenite and $\frac{1}{4}$ porphyroblastic cubic pyrite); one third anhedral quartz; one third sericitized albitic plagioclase; and one third interstitial chlorite, sometimes as pressure shadows of pyrite, defining a clear thin section-scale foliation. This is an albitic rock that yielded 6.04% Na_2O , the highest of any of the whole rock analyses done for this study. A K_2O content of 1.39% is probably entirely due to sericite; no K-spar was found.

A zone of interest in the sheared metabasalt and marked on the map is a thin interval rich in disseminated coarse magnetite coexisting with randomly oriented coarse cubic pyrite that appears to have developed porphyroblastically without pressure shadows in a low strain environment. Another is a few feet of sheared greenstone with minor iron carbonate, a trace of fine disseminated pyrite and rare malachite spotting.

This exposure has been sampled for gold more than once by MPC; the locations of the latest three grab samples are shown on the map. None of the samples yielded gold above detection limits. Despite the favorable-looking shearing, the lack of significant accompanying carbonate alteration may be an important reason for the lack of detectable gold in it, even where copper minerals are present.

Figure 14, the Jensen plot for the whole rock samples taken from this exposure, illustrates that the greenstone samples, regardless of degree of shearing, plot closely together in the high iron tholeiite field. Our sample of the tonalite porphyry from here is shown repeated on the Jensen plot of Figure 16 for the purpose of comparison with two other felsic intrusive bodies in this vicinity, the Mockler tonalite (sample "MOCK") and the tonalite porphyry at the Peninsula mine (sample "PG-1"). (Note: Accessory zircon was noted in thin sections of all of these rocks).

The shearing seen here cannot be traced eastward, and can be traced westward only a few hundred feet, where it is partially exposed in the old highway cut. Beyond that point, scattered outcrops in the hills to the west are of unfoliated metabasalt. The ductile shearing seen at this stop might represent only a branching splay of the Carp River Falls shear zone, whose main expression may well lie south of here at the Proterozoic contact.

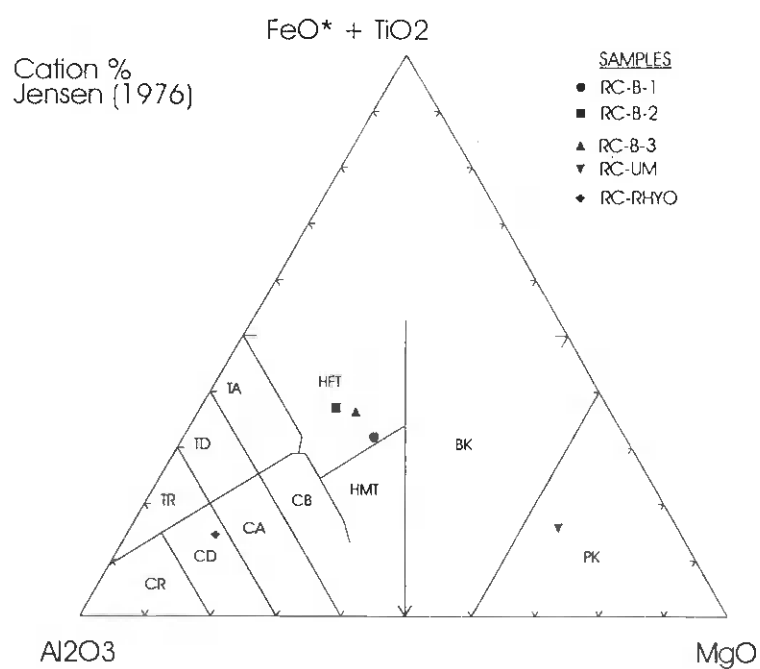


Figure 14: Stop SG-8

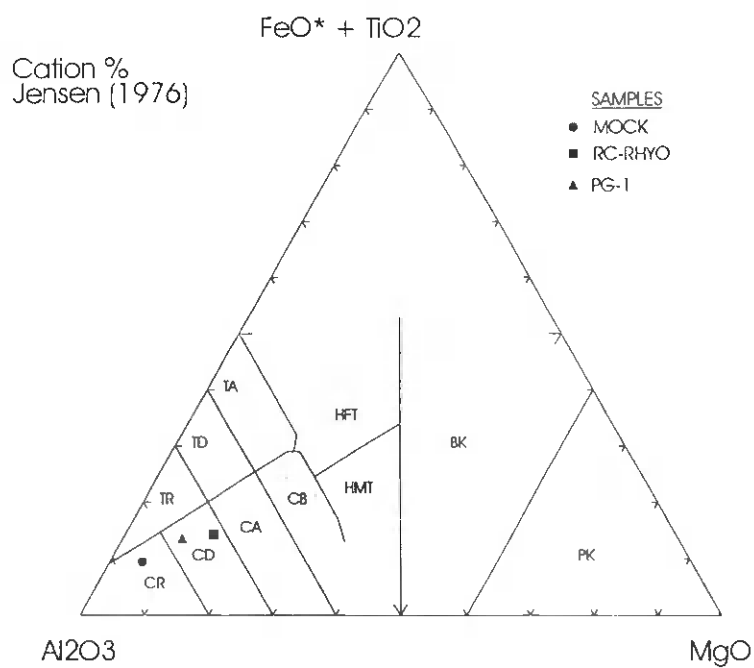


Figure 16

Stop SG-9: Peninsula gold deposit (Location map, Figure 12).

In contrast to the broad anastomosing ductile shear zones seen so far on this field trip, the Peninsula gold deposit occurs in a discrete brittle-ductile structure. Also in contrast to the nearly east - west regional shear zones seen so far, the Peninsula structure strikes north - northeast. This structure cuts a variety of host rocks, regionally mapped as Precambrian W massive and layered felsic rocks by Cannon and Klasner (1977) and subsequently assigned to the informal basalt flow unit of the Kitchi Formation (Bornhorst and Johnson(1993). At a scale useful for exploration, the geology is quite complex.

History

Gold was discovered at the Peninsula in the 1880's, but there was never any commercial production. All information on this period consists of old newspaper articles with very little useful technical data except the probable depths of the two old main shafts on the property, 69 feet for the North shaft and 80 feet for the South Shaft (Fountain, 1992). There was no modern-day activity at the Peninsula until it was purchased by Callahan Mining Corp. in 1981. MPC purchased the tracts encompassing the Peninsula and the nearby Michigan gold mine from Callahan in 1995; included in this acquisition were all of Callahan's drill core, exploration data and internal reports on these properties. The following synopsis of the work done by Callahan is based on an analysis and summary of this acquired data in part of a detailed report for MPC (Duskin, 1997).

Between 1981 and 1984 Callahan conducted surface reconnaissance mapping, rock sampling and geophysics. An early phase, called the "granitoid program" was focused on intensive chip and channel sampling of the tonalite porphyry, thought to be a pluglike intrusion with potential for large tonnage, open pittable gold mineralization. Disappointing results led to a re-focus on the steeply dipping "siliceous exhalite" originally tested by the oldtimers, termed the "Target Zone" by Callahan. The subsequent testing program consisted entirely of angle core drilling. No detailed mapping or trenching were done. Three shallow test holes under the old workings in 1984 returned sub-ore grade assay results but encouraging thicknesses. In 1985 the fourth hole, under the old South Shaft, returned 15.6 slant feet grading .216 oz/ton Au. Intensive close spaced drilling was then carried out through 1987, resulting in about 20,000 feet of core in a total of 37 holes. During the course of this drilling a presumed blind *en echelon* stratabound zone of mineralization, termed the "Back Zone", was discovered.

The purpose of the drilling was to quickly prove up a ramp-minable shallow tonnage of high grade ore to augment or eventually replace the ore being fed to the mill by the Callahan's mining operation

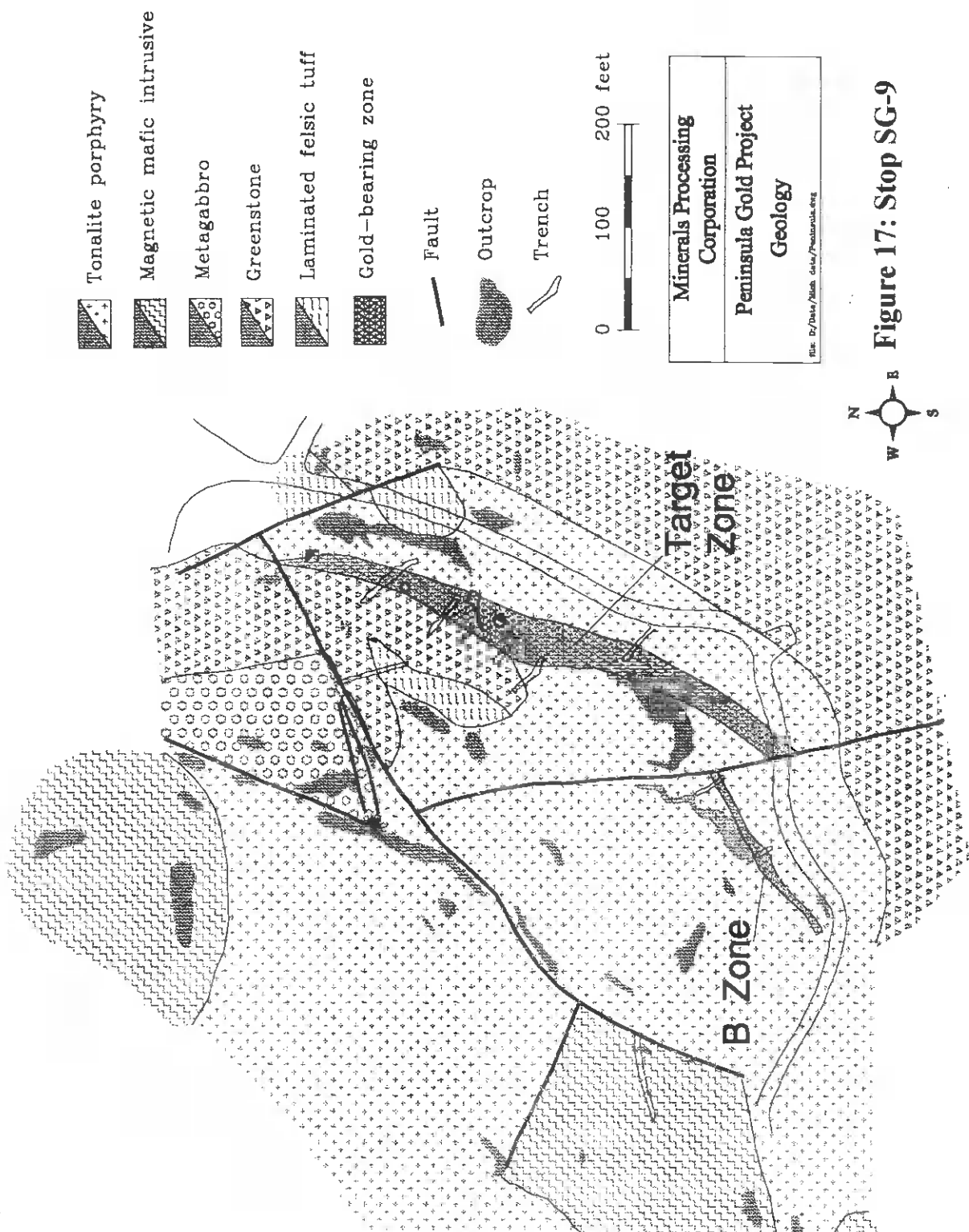


Figure 17: Stop SG-9

at the Ropes deposit. There was no attempt at stepout drilling, and the deposit remains open at depth and in both directions along strike. Callahan eventually calculated a reserve of 51,700 tons grading .141 oz/ton in the outcropping Target Zone segment of the structure, and an additional 41,200 tons grading .082 oz/ton in the Back Zone. Mining plans went as far as obtaining a mining permit in 1988 from the first level of authority, Marquette County. But the declining fortunes of the Ropes mine and of the corporation itself led to a suspension of activity at the Peninsula from then until the sale to MPC.

Taking a new approach not influenced by the stratabound gold models in vogue in the early 1980's, MPC began its re-evaluation of the property by rock sampling and mapping on a grid at 1"=100' in 1996. This led to the discovery of the Back Zone in outcrop (now renamed the "B Zone"), and the recognition that it is simply a fault offset of the Peninsula structure. Further work included digging and channel sampling 11 backhoe trenches, detailed 1"=20' mapping along the entire exposed structure, petrographic and polished section studies of mineralized core intervals, complete re-logging of many of the core holes, and correlation of the revised core log geology with the surface mapping. Figure 17 is a geologic map compiled from this work.

Lithology

The oldest of the rocks hosting the deposit area appear to be an interlayered sequence of greenstones and a laminated felsic tuff/fragmental unit. The tuff/fragmental is non-magnetic and erosionally recessive. Only one very small outcrop just east of the North Shaft can be found on surface; it was also encountered in Trench 7 northwest of there. In drill core this gray rock is extremely well banded and often carries coarsely fragmental heterolithic layers. It exhibits graded bedding, but tops and bottoms in this sequence have not yet been worked out. The greenstones are typical metabasalts and often exhibit amygdules in drill core. The many structural dislocations in the immediate Peninsula vicinity make it difficult to determine a strike trend for these units, but a distinctive bedded chert horizon within this sequence that outcrops about 1000 feet northwest gives an attitude of 035°, 72°SE.

The coarse grained metagabbro west of the North Shaft appears to be a small plug or sill intruding the greenstone; it contains large angular fragments of greenstone. This metagabbro is non-magnetic and completely amphibolitized, with pseudomorphs of calcic amphibole after orthopyroxene faintly preserved. It contains 2-5% coarse cubic porphyroblastic pyrite that often hosts microscopic inclusions of chalcopyrite; tiny free grains of chalcopyrite are also present in traces. The rock contains about 5% chlorite replacing amphibole, indicating retrograde metamorphism.

The most erosionally resistant of the Peninsula structure host rocks is the tonalite porphyry. This rock has been affected by both metamorphism and hydrothermal processes, especially where it lies close to the auriferous structure, where gold values ranging from a few to a few hundred ppb can often be found in it. In mapping near this structure, it is often difficult to distinguish a division between the two alteration effects, but one of the principal hallmarks of the hydrothermal alteration is an increase in chlorite as replacements, seamlets, enhanced foliation partings and slickensides. Other such effects are elevated content of fine grained disseminated pyrite, carbonate replacement of the groundmass, and white quartz veining. Strong alteration seldom persists for more than a few feet from structural contacts.

The porphyritic nature of this rock is often too subtle to readily discern in hand specimens, even in relatively fresh samples. In thin sections of these, the phenocryst content varies from 5% to 30%, and these are all heavily sericitized, corroded albite-oligoclase crystals. The groundmass has about 20% anhedral quartz, within a very fine grained mixture of biotite altering to chlorite, chlorite, albite, muscovite/sericite, and opaques consisting primarily of rutile and pyrite. Very rare tiny grains of probable molybdenite have been found in a few hand specimens. In one polished thin section of altered tonalite, microscopic inclusions of mixed chalcopyrite-pyrrhotite were found in pyrite.

Because of its relative erosional resistance, this unit has been "overmapped" in the past, and is probably also somewhat overmapped as depicted on Figure 17. In several drill holes passing under outcrops of tonalite, none was encountered in the subsurface. In some of the trenches it was found that low areas surrounded by outcrops of tonalite were underlain by subcrop of the older greenstone-tuff sequence that this hypabyssal intrusive invades. In drill core intercepts, its contacts with this sequence are usually brecciated and/or slickensided, but a few of them show injections of the tonalite into the greenstone. The tonalite porphyry is not a massive plug, but rather a cluster of dikes/sills.

The youngest rock unit is mapped as "magnetic mafic intrusive", but it is probably a metadiabase. This black rock is very weakly foliated (except immediately adjacent to contacts), exhibits an equigranular texture, and contains megascopic fresh biotite. It carries a few percent coarse euhedral pyrite, as well as ubiquitous disseminated magnetite, sometimes up to 10%. In drill core it contains trains and screens of angular fragments of the tonalite.

Structure and Mineralization

The Peninsula fault structure affects all of the rock types, inclusions of which can be found within it. We recognize two basic lithotypes within the structure: quartz-carbonate ("q-c"), and chlorite-carbonate-pyrite ("ccpy"). Angular breccias are common in the q-c lithotype. Host rock fragments are less abundant, but sometimes present in the ccpy lithotype, usually as boudins. The q-c lithology predominates where the fault structure intersects tonalite, primarily in the Target Zone; it exhibits mostly brittle textures and has abundant albite as veinlets and breccia matrix. The primary carbonate is dolomite, with lesser ankerite, rhodochrosite and late calcite. Silica content is highly variable. The q-c usually contains chloritic slip planes, and sometimes lenses or interfingering layers of ccpy. Megascopic metallic minerals in the q-c are pyrite, very minor chalcopyrite, and, rarely, visible gold. There is a strong correlation of gold assays with pyrite, but it is not 1:1. In microscope examination of high gold - high pyrite samples, gold is found as tiny inclusions in pyrite, either alone or with sphalerite. Other inclusions in pyrite are argentiferous galena, pyrrhotite and chalcopyrite. In low pyrite samples with visible gold, the gold appears to be later than pyrite, occurring as free grains in chlorite and carbonate, associated with chalcopyrite.

The dominant mineral in the ccpy lithology is chlorite, and this rock characteristically displays ductile textures. This lithology seems to dominate the fault zone where it intersects greenstone or metadiabase, both in the B Zone segment and in the deeper levels of the Target Zone segment. There is albite in the matrix of this rock, but virtually no quartz. In the B Zone, most of which involves faulting adjacent to the metadiabase, much of the chlorite can be seen in thin section to be replacing biotite. The ccpy is generally much higher in pyrite than the q-c, and also contains several percent magnetite in the B Zone segment, probably derived directly from the metadiabase. In polished section magnetite and pyrite exhibit coexisting mutual textures. Chalcopyrite also occurs as a minor sulfide in this lithology. Gold, where found so far, occurs as inclusions in pyrite, and in quartz and carbonate veinlets.

The clear impression is that the composition of the Peninsula gold structure's gangue is very host rock-dependent. It appears that a great deal of host rock has been assimilated into the structure, with the availability of free silica in the metatonalite contributing to the quartz in the q-c lithology. Similarly, the lack of free silica and the abundance of ferromagnesian in more mafic host rocks promoted the development of chlorite where those rocks were intersected. The abundance of dolomite in the q-c and of chlorite in the ccpy indicates a very strong introduction of magnesium into the hydrothermal system that operated within the Peninsula fault structure.

The Target Zone strikes 020° and dips steeply SE. On the southwest it is offset by a later high angle fault which also rotates it into an orientation trending 050°, still dipping steeply SE (the B Zone). Vertical movement on this cross fault has exposed the gold structure here at a different depth level, involving mostly the magnetic metadiabase in its footwall instead of the tonalite porphyry. Where intersected in drilling, late faults such as this one consist of narrow zones of breccia. These faults form an interconnecting pattern. Their traces in some cases yield anomalous gold in grab sampling, but it's not clear whether this represents a later mineralizing event or mineralization remobilized from the Peninsula structure.

Stop SG-10: Michigan Gold Mine (Location map, Figure 12).

MPC has done only a limited amount of work so far on this gold occurrence. It is included as an optional field trip stop if time permits. There are very few outcrops in the immediate mine vicinity; most of them are metabasalts of the Kitchi Formation informal basalt flow unit, cut by tonalite porphyry similar to that at the Peninsula mine. These rocks are cut by at least five parallel, east-west, nearly vertical quartz veins. Compared to other gold deposits in this area, the Michigan veins are very low in pyrite, and represent a low sulfide hydrothermal system. There is no particular correlation of gold with pyrite, and this deposit represents a case of severe nugget effect. These veins are famous for carrying free gold, which can only be found today through very diligent effort on the old mine dump. Examination of the dump rocks and three core holes drilled by Callahan in the 1980's shows that the veins represent brittle structures. Angular breccia is common, as are open space filling textures. Black tourmaline is a common vein mineral here; other exotic minerals found here include coarse molybdenite, powellite, scheelite, chalcopyrite and a bismuth telluride. This mineralogy is typical of the igneous assemblage often found in the roots of porphyry copper deposits.

Recorded 19th Century production from here was 856 ounces of gold. Most of this appears to have come from the No. 6 Shaft on the "main" vein, which was mined from the 55-foot level upwards. According to records inherited with the property by MPC, nothing happened at this mine again until the 1930's, when a financially struggling small local stock company deepened the No. 6 to 250 feet and drifted laterally east and west along the vein. The blocked-out ore was never mined except for bulk sample tests. It is not clear exactly where in the mine the bulk samples came from. The reason that the bulk tests were done is that the company's underground grab and channel samples all showed extreme

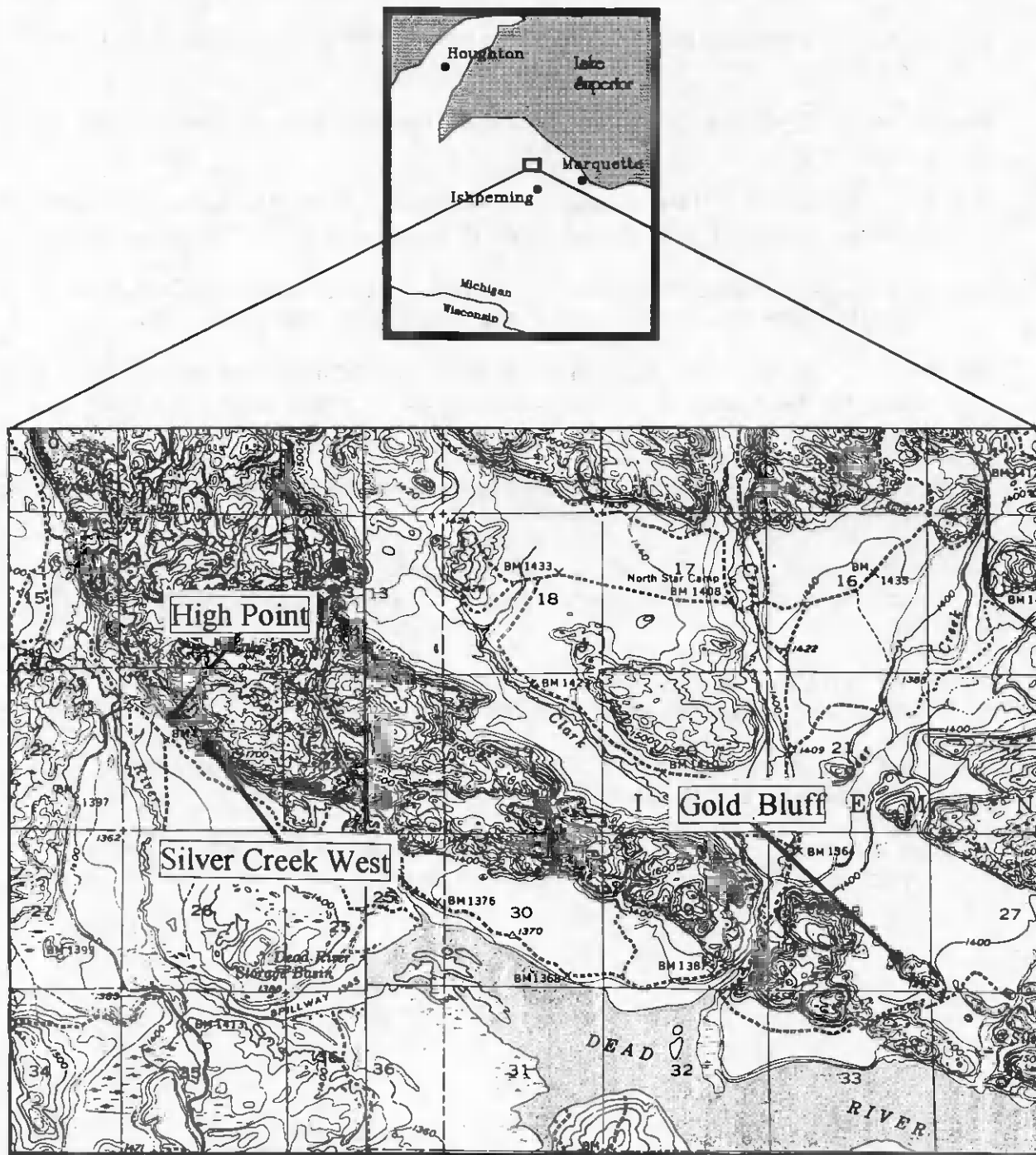
assay variability. Two bulk tests, first of a 1-ton sample and then of a 10-ton sample, were done in Houghton by Michigan Tech., which determined a grade of approximately .3 oz/ton Au. A third test was done in 1937 at a flotation mill on-site under the supervision of Michigan Tech.. This also indicated a grade of .3 oz/ton. At this point the stock company tried to pay its debts and move to commercial mining by floating a new stock issue in a difficult financial and regulatory environment. The various records and correspondence in MPC's files show that this company was still trying to get approval to market its stock as late as the summer of 1941. As soon as World War II began, the War Production Board prohibited all gold mining in the U.S.; nothing apparently ever happened at the Michigan after that except the three core holes drilled by Callahan.

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**Examples of Gold Mineralization in the Northern
Block of the Ishpeming Greenstone Belt**

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Minerals Processing Corporation, Champion MI**



Minerals Processing Corporation's High Point, Silver Creek West, and Gold Bluff gold properties all lie in the northern arm of the Ishpeming greenstone belt. The field trip stops are intended to illustrate the various styles of gold mineralization found in this part of the belt. Host lithologies, structure, controls of mineralization, and alteration will be discussed and compared.

High Point Gold Prospect

The High Point prospect was discovered by MPC during reconnaissance exploration activities working out from Callahan Mining Corp's Silver Creek West occurrence located 1500 ft. to the southeast. High grade surface mineralization at High Point is hosted by a prominent knob of intrusive felsic porphyry along the topographic escarpment of the Dead River Shear Zone (DRSZ). Subsequent exploration activities at the prospect included detailed mapping and sampling, geochemical surveys, trenching, and diamond drilling. Figures 1 and 2 show the geology of the High Point prospect.

Lithology

Rock types at the High Point prospect consist of felsic, porphyritic intrusive rocks, within a sheared sequence of mafic flows and tuffaceous rocks and minor interflow sediments corresponding to the Lighthouse Point Basalt of Johnson and Bornhorst (1991). The High Point intrusive is a fine to medium grained, massive to weakly foliated feldspar porphyry stock consisting of small phenocrysts of albite in a matrix of quartz, albite, potassium feldspar and carbonate. In addition to the main stock, numerous thin stringers of porphyry of similar composition are present in the surrounding volcanics. These mafic volcanic rocks consist of fine grained, chlorite, sericite, and amphibole schists, and are probably altered basalts and related tuffaceous rocks that have been variably sheared and deformed.

Structure

All rock types at the High Point prospect have been subjected to shearing and deformation related to the DRSZ. Mafic units exhibit steeply dipping shear related foliations striking NW-SE, parallel to the main DRSZ, as well as E - W striking ancillary shearing oblique to the main DRSZ trend. This shearing is well exposed in backhoe trenches 1 through 3 (see Figure 2), which expose the flanking volcanic section adjacent to the High Point intrusive. The High Point Intrusive body and related sills and dikes exhibit intense brittle deformation manifested by irregular stockwork fracturing, quartz - carbonate veining, and brecciation. Irregular contacts of these felsic units observed in drill core, as well as a lack of continuity between porphyry units in outcrops, drill holes, and trenches, suggest that these felsic units have been extensively disrupted and possibly rotated as large competent blocks within this portion of the DRSZ.

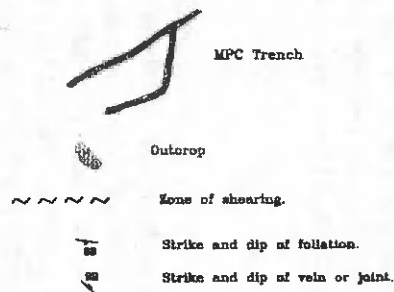
Alteration

Ubiquitous carbonate alteration consisting of calcite and dolomite-ankerite is present throughout the sheared section at the High Point Prospect, occurring as a pervasive replacement of rock matrix, and as discrete veins and fracture fillings in both mafic and felsic units. Coarse, secondary muscovite, as well as an unknown black shiny carbon mineral are commonly associated with carbonate veining in the High Point area. Examples of the carbon mineral can be readily found in the talus slope below the mineralized outcrops of High Point intrusive, and drilling has revealed that this mineral is present throughout the

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Geology of the High Point Prospect

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High Point Intrusive

Feldspar Porphyry. Fine to medium grained, reddish brown porphyritic rock composed of 1 to 5 mm albite phenocrysts in a matrix of albite, K-feldspar, quartz, muscovite and carbonate. Pervasively fractured, and veined with quartz, ferroan dolomite, ankerite, and an unknown black carbon mineral.

High Point Intrusive

Sericite and carbonate altered porphyry, cut by irregular stockwork veins and masses of gray quartz, iron carbonates, minor pyrite, minor galena, bismuth tellurides, and gold.

Basalt, Andesite

Fine grained chlorite, sericite, carbonaceous schists. Massive to foliated and fractured with stockwork carbonate - carbon mineral veins and disseminated pyrite where sheared. Locally containing gray quartz veining and gold mineralization. Sequence contains minor interflow cherty, pyritic sediments.

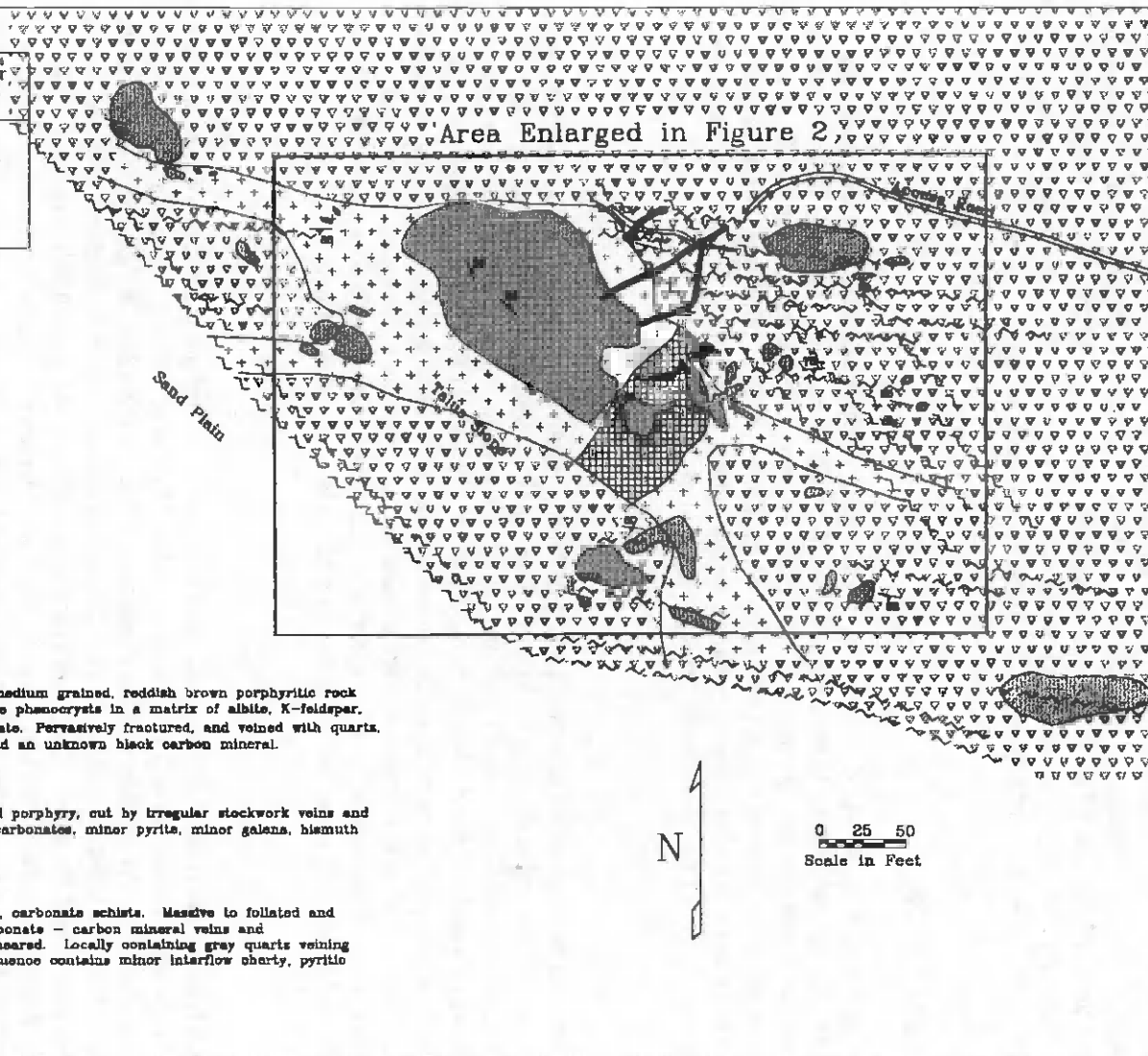


Figure 1. Geology of High Point

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Gold Values (ppb)
Channel Chip and Trench
Samples

\\msr-dc\DATA\Mahi-gan Data\Section 23\High Point Carol Udd

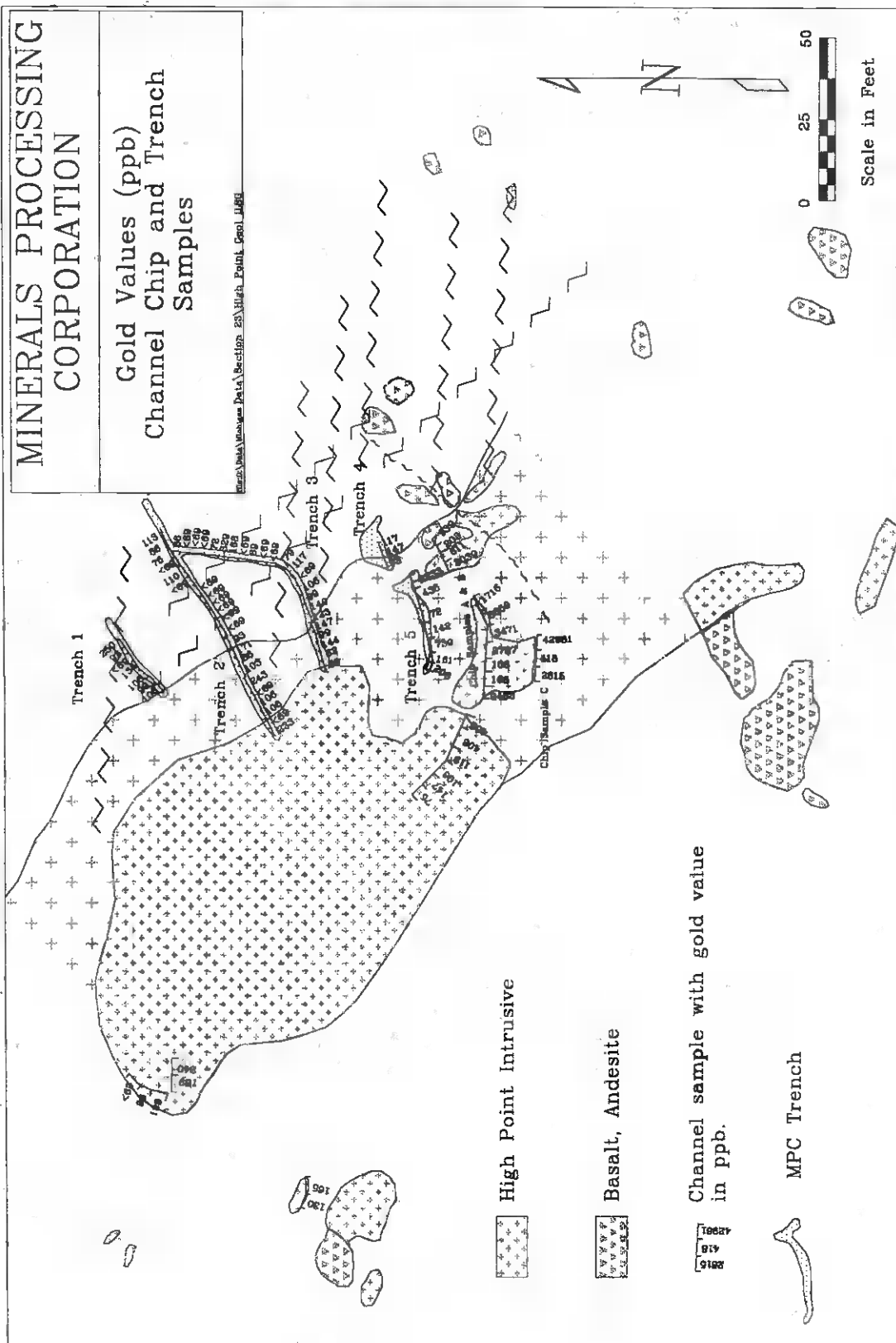


Figure 2. Detailed Geology of High Point

flanking volcanic section as well. Within the mineralized portion of the High Point intrusive, microprobe analysis has shown that zoned dolomite-ankerite is intimately intergrown with barium bearing K-feldspar and muscovite. Tourmaline is also locally present in quartz veins, in the matrix of brecciated porphyry, and intergrown with chlorite along fracture surfaces in sheared volcanic rocks.

Mineralization

Surface mineralization at High Point is confined to the porphyry, and consists of irregular gray quartz veining in altered porphyry on the southeast side of the main knob. Here channel chip sampling of exposed outcrops (Chip Samples A, B, and C) returned significant gold values including 28 ft. of .09 oz/ton, and 14 ft. of .35 oz/ton including 4 ft of 1.25 oz/ton (Figure 2). The mineralized quartz from these exposures is dark gray, cut by iron carbonate veinlets, and contains small amounts of pyrite, chalcopyrite, galena, sphalerite, and electrum as well as an exotic suite of bismuth tellurides, lead bismuth tellurides, and an unknown lead-bismuth-silver sulfide. The geometry of this mineralized zone has not yet been defined, although its extent has been partially confined by trenching and wide spaced drilling.

Silver Creek West

Silver Creek West is a gold occurrence within variably altered and foliated mafic rocks. In 1988 Callahan Mining Corporation calculated a resource of 1.1 million tons @0.037optAu for Silver Creek West but never exploited it because of unresolved concerns over gold continuity and controls. Surface trenching exposes gold mineralization in ductile sheared and carbonate-chlorite-sericite-pyrite altered basalt near the margin of a felsic porphyry. In drill hole intersections, mineralization appears to be stratabound within 170 foot section of moderately carbonate altered, massive medium grained mafics. Mineralization in both trenches and drill core will be observed at this stop. The general geology of Silver Creek West is shown in Figure 3.

Lithology

The lithologies in the immediate vicinity of the Silver Creek West prospect consist of a number of generally northwest striking, steeply dipping units, largely of the Archean Lighthouse Point Basalt (Johnson and Bornhorst, 1991). To the northeast of the SCW prospect is a large expanse of fine grained, pillowed basalt. Nearer to the prospect occurs a medium to fine grained equigranular chlorite-albite-carbonate unit, variously interpreted as an ophitic basalt, a sheared carbonated basalt, and a hypabyssal mafic intrusive or sill. The unit is generally massive, contains significant pyrrhotite and hosts gold mineralization at depth in drill core. The next unit to the southwest is a narrow band of chlorite-albite-sericite-carbonate phyllite interpreted as a ductile sheared basalt. This unit hosts gold mineralization exposed in surface trenches. This basalt is bounded to the southwest along the cliff face by a rhyodacite porphyry which consists of quartz, feldspar, and chlorite phenocrysts in a felsic groundmass. Drill intercepts show an additional sequence of chlorite-albite-sericite phyllite and quartz-feldspar intrusive to the southwest. In at least one hole the latter felsic is in fault contact with Proterozoic sediments which have been down-thrown to form the basin to the southwest.

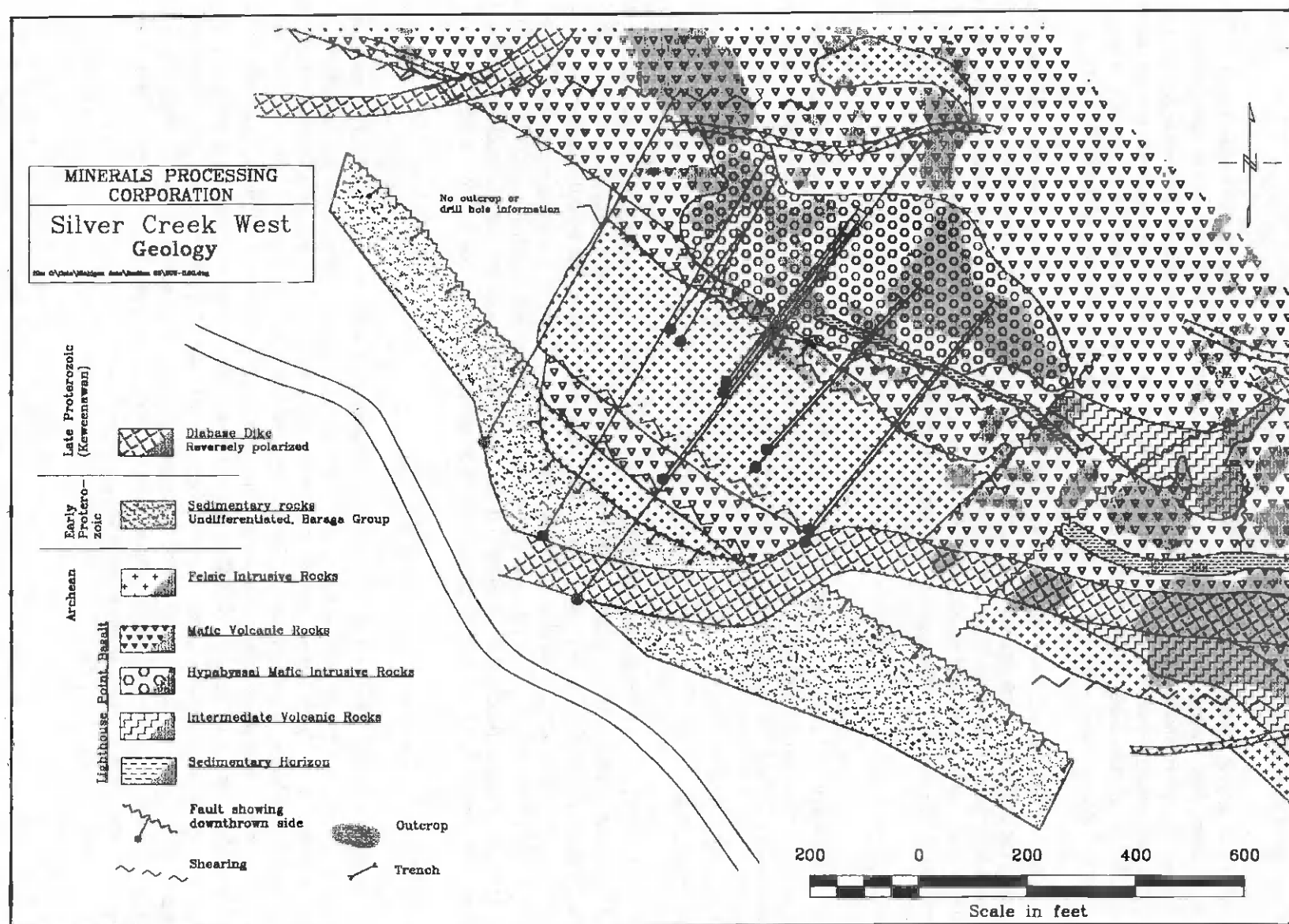


Figure 3. Geology of Silver Creek West

Structure and mineralization

At the surface, gold mineralization exposed in trenches by Callahan occurs within a ductile sheared mafic volcanic near the margin of a felsic porphyry. This shearing strikes 300° and mineralization is considered C-type replacement. In contrast to surface exposures, mineralized intervals in drill core are in an unfoliated, weakly altered medium grained mafic unit; there is little resemblance to mineralization in the sheared basalt. Gold-bearing intervals that in drill intercepts occur at depth to the east/northeast from the trenched intervals do not project upwards along obvious structural planes to the surface workings.

The exact controls to the mineralization at depth have not been proved. Intersection lineations of various structural features plunge down to the east and offer one possible explanation for joining surface and drill-hole gold (Johnson, 1991). Limited work by MPC has shown that anomalous mineralization occurs in outcrop to the east of the high grade trenches at the up-dip (along S1 foliation) projection of the mineralized drill core intervals, suggesting that the trench and drill core intercepts are not connected.

Alteration

The mineralized zone is associated with weakly disseminated calcite+chlorite+sericite+pyrite alteration. Locally, minor Fe-carbonate is observed at surface and in felsic units encountered in drilling. Additionally, Callahan geologists identified an early epidote-pyrrhotite (spilite) event in the basalts.

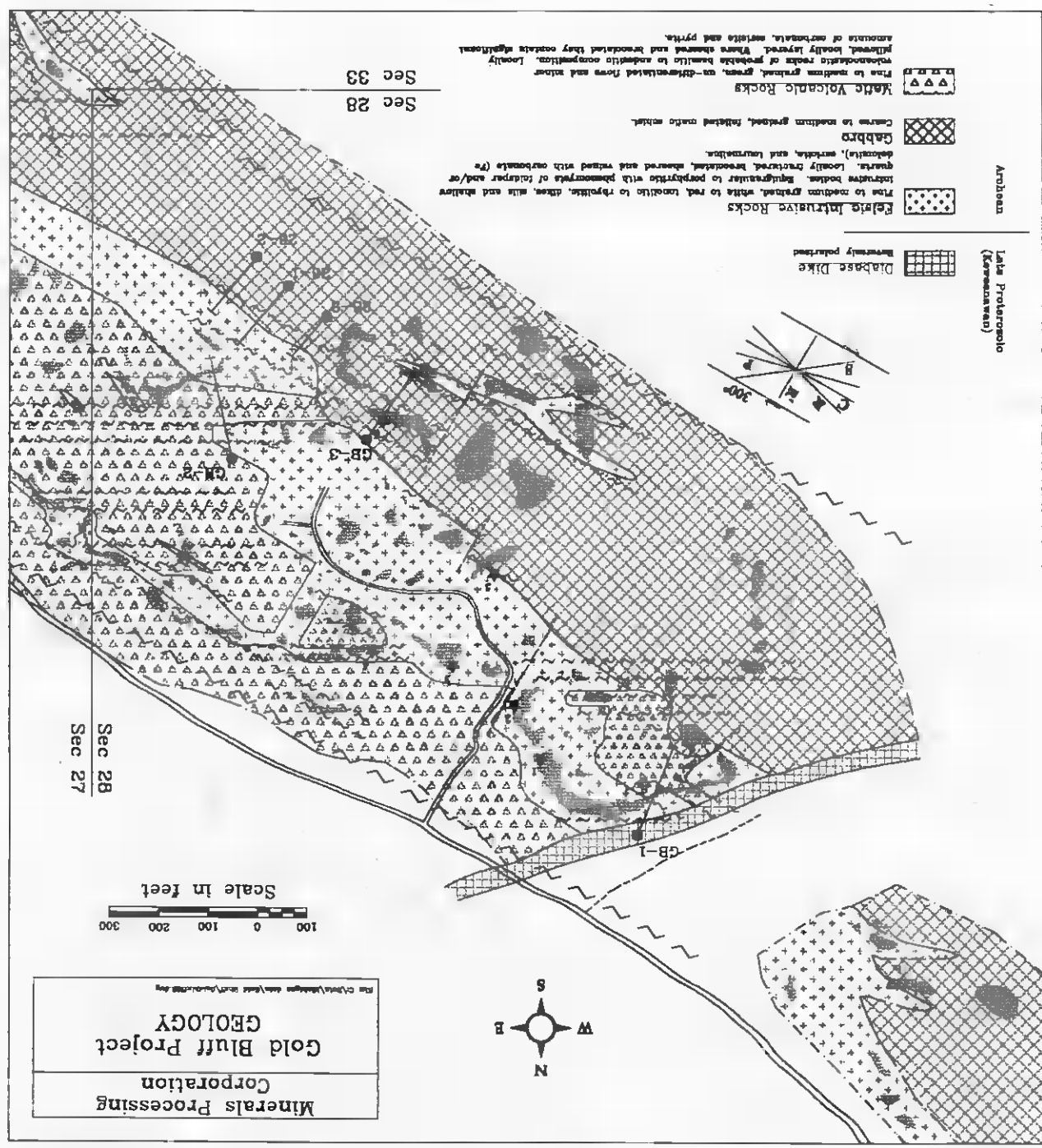
Gold Bluff Prospect

Gold Bluff is one of Minerals Processing Corporation's active gold properties (see Figure 4). Gold Bluff is located within a 300° trending, 1000 foot wide shear zone in mafic volcanics. A 100 to 200 foot wide felsic porphyry (the GB porphyry) intrudes the shear zone. Within the bounding shear occur east-west and northeast striking mineralized subsidiary shear zones. Outcrop sampling routinely yields gold in the 1ppm to 10ppm range. Trenching and drilling in 1998 intersected significant widths of disseminated low grade gold mineralization the GB porphyry and higher grade gold in mafic host rock. Mineralization in both mafic and felsic hosts in different structural orientations will be seen at Gold Bluff.

Lithology

Three lithologies are found at Gold Bluff: fine-grained mafic volcanic; medium to coarse-grained mafic volcanic, referred to as a gabbro; and felsic porphyry. The mafic units are metamorphosed to greenschist facies and both can be massive to strongly foliated. They belong to Lighthouse Point Basalt as described by Johnson and Bornhorst (1991). The felsic unit is a rhyodacite porphyry interpreted as intrusive. Where it appears to be a continuous unit that divides the two mafic units, it is dubbed the GB porphyry. Smaller felsic dikes are also observed in various orientations throughout the property. Contacts strike northwest and have steep dips. A reversely polarized dike of Keeweenawan age is interpreted from magnetic data to lie just to the north of the outcropping rocks. The only other unit of significance in the area is the Reany Lake Pyroclastic (Johnson and Bornhorst, 1991) which occurs just off the Gold Bluff property to the north and west in association with gabbro flows.

Figure 4. Geology of Gold Bluff



Structure

The orientation of brittle and ductile shear structures, felsic porphyries, and quartz veins is geometrically consistent with a system of conjugate shears that control gold mineralization. Bounding shear features, mostly penetrative foliation in mafic rocks and along felsic contacts, strike 300° . Within this, subsidiary structures and a variety of mineralization styles are observed. For example, the GB porphyry trends 320° and appears to occupy an oblique shear position (probably R-type Reidel). Mineralization in Trench 5 and DDH GB-3, and along felsic contacts, strikes 300° and is C-type replacement veining. R'-type shears are present as northeast striking ductile micro-shears and as numerous mineralized quartz veins. Numerous ductile shears and minor felsic porphyries that strike 080° to 100° may be either P or S-type structures.

White quartz-carbonate-tourmaline veins with fibrous structure perpendicular to the vein walls are interpreted as extensional features. These typically dip in the 30° to 40° range and indicate a high angle component to the shearing event responsible for these veins. Gray quartz veins are often mineralized, deformed, and cross-cut by white quartz veins indicating multiple shearing and vein deposition events.

Alteration

A zoned carbonate alteration halo occurs at Gold Bluff. Distal alteration in the mafic volcanics consists of disseminated calcite and weak Fe-carbonate, (ankerite-dolomite). As the GB porphyry is approached, Fe-carbonate increases and can be pervasive to the point of flooding and the assemblage sericite+white quartz+pyrite+tourmaline appears, largely in the felsics. Lithologic textures are generally intact. Within the GB porphyry a zone of strong sericite+pyrite+Fe-carbonate occurs with porphyritic textures sometimes completely replaced by fine grained sericite.

Mineralization

Mineralization occurs in all three lithologies and consists of quartz+gold+pyrite+Ag&Bi-tellurides. In the metabasalts C-type replacement mineralization (i.e., highly silicified and sulfidized zones with narrow foliation-parallel quartz veins, lenses and pods) is generally confined to thin ductile shears at or proximal to felsic contacts. Similar, although often higher grade, mineralization occurs at the gabbro/felsic contact. Significant C-type vein mineralization not associated with a felsic contact also occurs within sheared gabbro south of the GB porphyry (8.7'@0.188 opt Au and 17'@0.077 opt including 7.5'@0.148opt w/VG).

In the GB porphyry, mineralization is found in quartz vein stockwork and tends to be associated with disseminated pyrite and strong alteration. Gold-bearing veins are gray colored compared to barren white quartz-carbonate-tourmaline veins, although white quartz veins are an important indicator. One gray quartz vein 0.4 feet wide assays 20-50 opt Au and has yielded impressive visible gold specimens. Recent drilling in the GB porphyry by MPC intersected significant mineralization (224'@0.018opt including 11'@0.178 and 3'@0.122 opt).

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Field Trip 3

Tilden and Empire Mines of the Marquette Iron Range, Michigan

Leaders: G.W. Scott, P.M. Nordstrom and H.M. Lukey

Geologic Setting of the Tilden and Empire Mines, Michigan

Theodore J. Bornhorst, Department of Geological Engineering and Sciences, Michigan Technological University, Houghton, MI 49931

Introduction

The Tilden and Empire Mines are located in the Marquette Iron Range of Michigan's Upper Peninsula (Figure 1). Mining began at the Empire Mine in 1963 and at the Tilden Mine in 1974. This is the first Institute of Lake Superior Geology field trip to either of these iron mines. The Marquette Iron Range has had a long and varied mining history (Boyum, 1988). Iron mining began in the mid-1800's and current reserves are sufficient to sustain iron mining until at least 2030.

Stratigraphic Setting

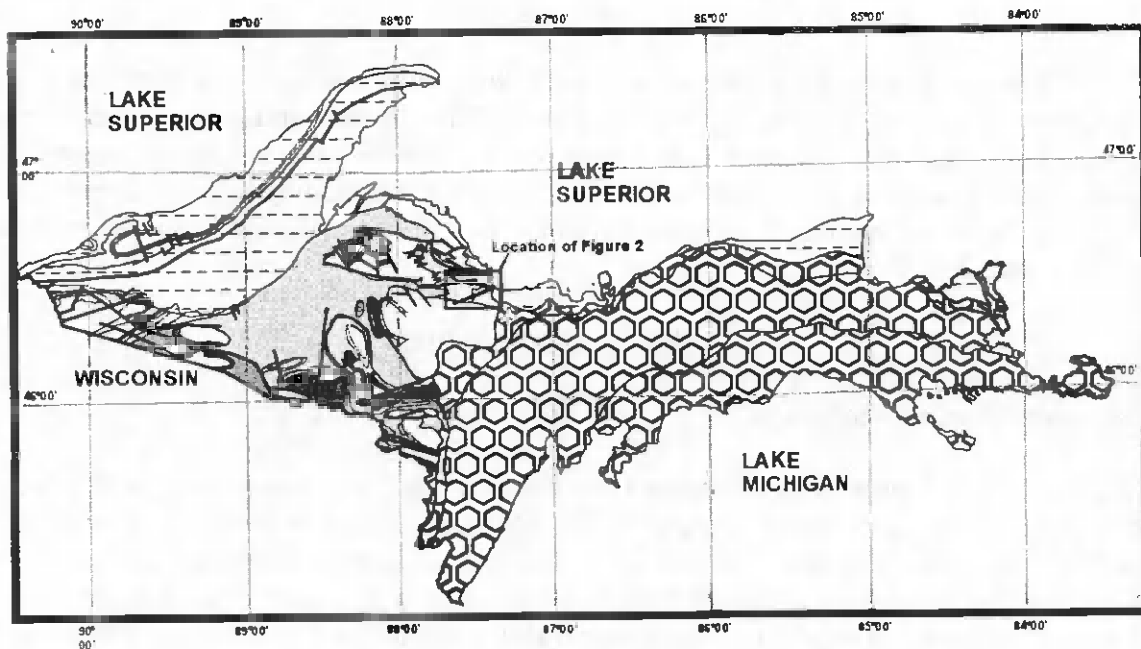
Marquette Range Supergroup

The Tilden and Empire Mines produce iron ores from the Early Proterozoic rocks of the Marquette Range Supergroup (Figure 2). The Marquette Range Supergroup consists of sedimentary rocks with minor amounts of volcanic rocks and is subdivided into three groups: Chocoday, Menominee and Baraga Groups, from oldest to youngest. The rocks of the Marquette Range Supergroup were unconformably deposited on older Archean basement.

The three groups of the Marquette Range Supergroup are separated by minor angular unconformities. The groups are subdivided into formal formations and informal units. The Chocoday Group consists, from the base upward, of conglomerate (Enchantment Lake Formation), quartzite (Mesnard Quartzite), dolomite (Kona Dolomite), and slate (Wewe Slate). The Menominee Group unconformably overlies the Chocoday Group and consists, from the base upwards, of local conglomerate, quartzite (Ajibik Quartzite), slate (Siamo Slate), and iron formation (Negaunee Iron Formation). The Baraga Group is the youngest of the three groups and unconformably overlies the Menominee Group. The Baraga Group includes a variety of stratigraphic units. In the Marquette area it consists, from the base upwards, of quartzite (Goodrich Quartzite), slate (Lower Slate of the Michigamme Formation), iron formation (Greenwood Iron Formation), mafic pyroclastics (Clarksburg Volcanics), iron formation, slate (Upper Slate of the Michigamme Formation), and iron formation (Bijiki Iron Formation). Iron ore has been mined from iron formations within the Menominee and Baraga Groups. However, most production has come from the Negaunee Iron Formation of the Menominee Group, including the Tilden and Empire Mines.

Diabase Dikes and Sills

The stratified units of the Marquette Range Supergroup are commonly intruded by Early Proterozoic diabase (metamorphosed) in the form of dikes and sills. Early Proterozoic diabase dikes and sills are particularly common in vicinity of the Tilden and Empire Mines. Diabase is also associated with the Clarksburg Volcanics of the Baraga Group, 10 to 20 km



EXPLANATION

Paleozoic



Undifferentiated Paleozoic Rocks

Keweenawan



Undifferentiated Keweenawan Rocks

Early Proterozoic



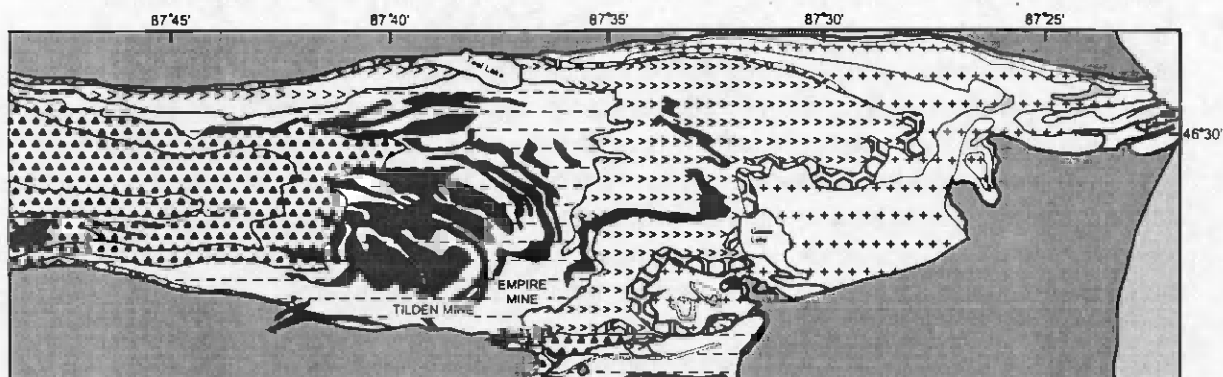
Undifferentiated Early Proterozoic Rocks

Archean



Undifferentiated Archean Rocks

Figure 1: Geologic setting of the Marquette iron range.



Explanation

Middle Proterozoic

 Keweenaw sandstone and diabase

Early Proterozoic

 Metadiabase

Marquette Range Supergroup

Baraga Group

 Undifferentiated

Menominee Group

 Negaunee Iron Formation

 Siamo Slate

 Ajibik Quartzite

Chocolay Group

 Undifferentiated

Archean

 Undifferentiated

Figure 2: Generalized geology in vicinity of the Tilden and Empire Mines.

west of the mines. Several geologists have suggested that Early Proterozoic diabase intrusions throughout the Marquette region are the same age as the Clarksburg Volcanics of the Baraga Group and younger than the Negaunee Iron Formation. However, some of the diabase sills at the Tilden and Empire Mines may have been lava flows (Scott and Lukey, this volume). This interpretation suggests multiple ages of Early Proterozoic diabase and mafic magmatism during the time of deposition of iron formation. The Hemlock Formation, south of the Marquette area in the Iron Mountain area, consists of mafic volcanics that is correlative with the Menominee Group (Morey, 1996). This supports the interpretation of mafic magmatism during the Menominee Group in the Marquette area.

Later Middle Proterozoic Keweenaw diabase (not metamorphosed) dikes also cut the rocks of the Marquette Range Supergroup and cut the Negaunee Iron Formation at the Tilden and Empire Mines.

Negaunee Iron Formation

The Negaunee Iron Formation consists of a variety of iron rich rocks in the Marquette area (Figure 2). The major types of iron formation are carbonate iron-formation (iron carbonate and chert with minor magnetite), oxide iron formation (hematite or magnetite and chert), magnetite-banded iron formation (laminated magnetite and chert), hematite banded iron formation (laminated hematite and chert), silicate iron formation (iron silicate minerals and chert) and combinations of these types (Gair, 1975). The Negaunee Iron Formation is described in detail by Scott and Lukey (this volume), Nordstrom (this volume), and Gair (1975). The origin of the iron minerals in the Negaunee Iron Formation is a complex combination of primary sedimentary depositional, diagenetic, and metamorphic processes.

The maximum thickness of the Negaunee Iron Formation is about 1150 meters, although folds and faults make thickness difficult to assess (Gair, 1975). The Negaunee Iron Formation is thickest in vicinity of the Tilden and Empire Mines where it occurs in the nose of a regional west plunging syncline about 6 km across (Figure 2).

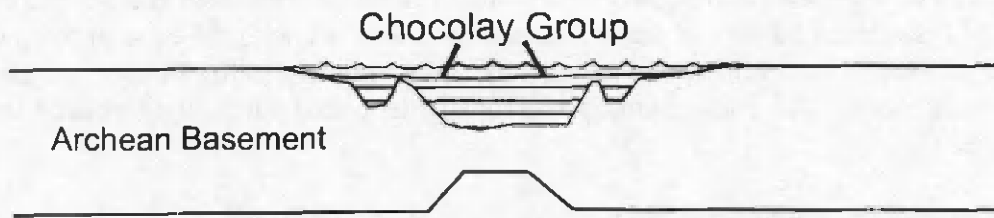
Age of the Marquette Range Supergroup

Morey (1996) has provided a stratigraphic synthesis of the Marquette Range Supergroup. Although the age of the onset of sedimentation of the Marquette Range Supergroup is uncertain, he has suggested that the Chocoma Group is younger than 2,219 $\pm$ 4 Ma. The age of volcanic rocks correlated with the Menominee Group is 1,910 $\pm$ 10 Ma. Deposition of the Baraga Group ended by 1,852 $\pm$ 6 Ma.

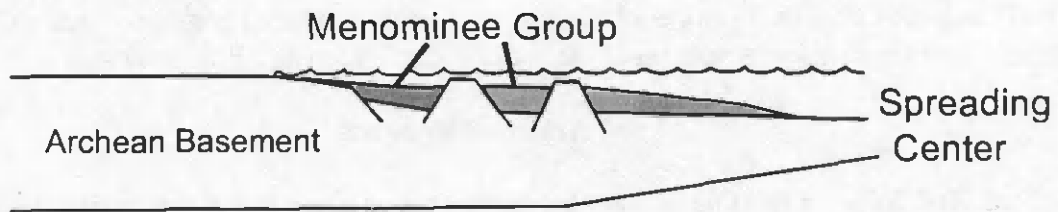
Depositional and Tectonic Setting

The Marquette Range Supergroup is interpreted to have been deposited in several stages (Morey, 1996; Schulz and others, 1993). The sediments of the Chocoma Group were deposited during a late intracratonic or intrarift stage (Figure 3). The sediments of the Menominee Group were deposited on a passive continental margin in normal listric fault bounded rift basins (Cambray, 1991). The Negaunee Iron Formation mined at the Tilden and

Late Intracratonic or Intrarift Stage



Rift Stage



Foredeep Basin Stage

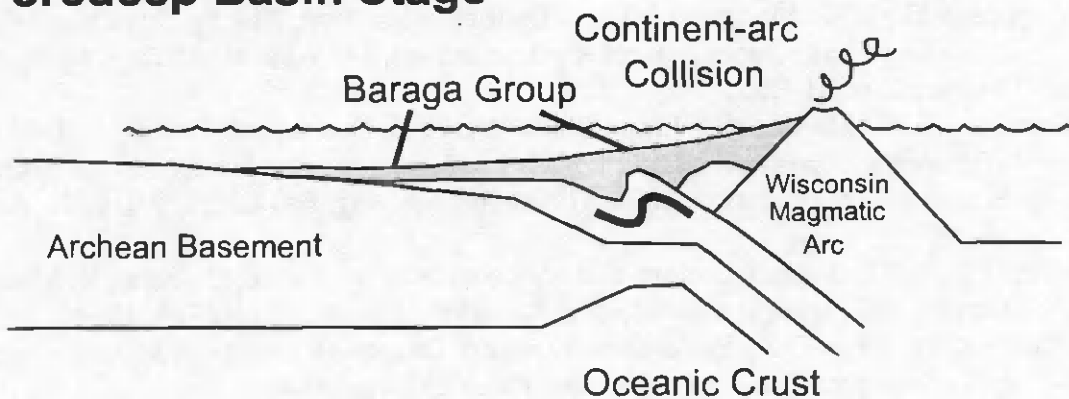


Figure 3: Depositional and tectonic setting of the Marquette Range Supergroup (modified from Morey, 1996).

Empire Mines was deposited during this stage and some faults at the mines may be related to this stage (Scott and Lukey, this volume). Elsewhere, and perhaps in the Marquette area too, tholeiitic basaltic magmatism also accumulated in these rift basins. The Negaunee Iron Formation depositional basin(s) are located along the Great Lakes tectonic zone, a late Archean suture zone (Sims and others, 1980). Passive margin deposition transitioned into deposition of sediments and minor volcanic rocks in a foredeep basin stage that formed as a result of Penokean collision of the Wisconsin magmatic arc with the edge of the continent (Morey, 1996). The continent-arc suture zone approximately follows the Michigan-Wisconsin border. The Baraga Group was mostly deposited during the foredeep stage as turbidites.

The Marquette Range Supergroup is within the fold and thrust belt of the 1850 Ma Penokean orogen (Sims, 1996). The Tilden and Empire Mines are located on the south limb of the Marquette Synclinorium, an east-west trending, west plunging syncline that is about 6 km across and 55 km long parallel to the fold axis. The synclinorium, like the Negaunee Iron Formation depositional basin(s), may have been controlled by the Archean Great Lakes tectonic zone. The iron formation and Archean structures were subsequently folded during the Penokean Orogeny. The Penokean orogenic event produced complex folds and faults and greenschist facies metamorphism of the rocks at the Tilden and Empire Mines

Acknowledgments

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GEOLOGIC FIELD TRIP TO THE TILDEN MINE

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Introduction

This geologic field trip to the Tilden Mine is designed to show the primary structural and stratigraphic features of the iron ore bodies and the implication of these geologic features in mine planning and ore control. The interaction of sedimentation and diagenesis within growth fault controlled basin, metamorphism and supergene oxidation has resulted in a complex suite of ore types, each with specific, if not entirely objective, blending characteristics and problems. Although the mining operation tends toward "brute force", some of the blending concerns can be quite subtle and sensitive.

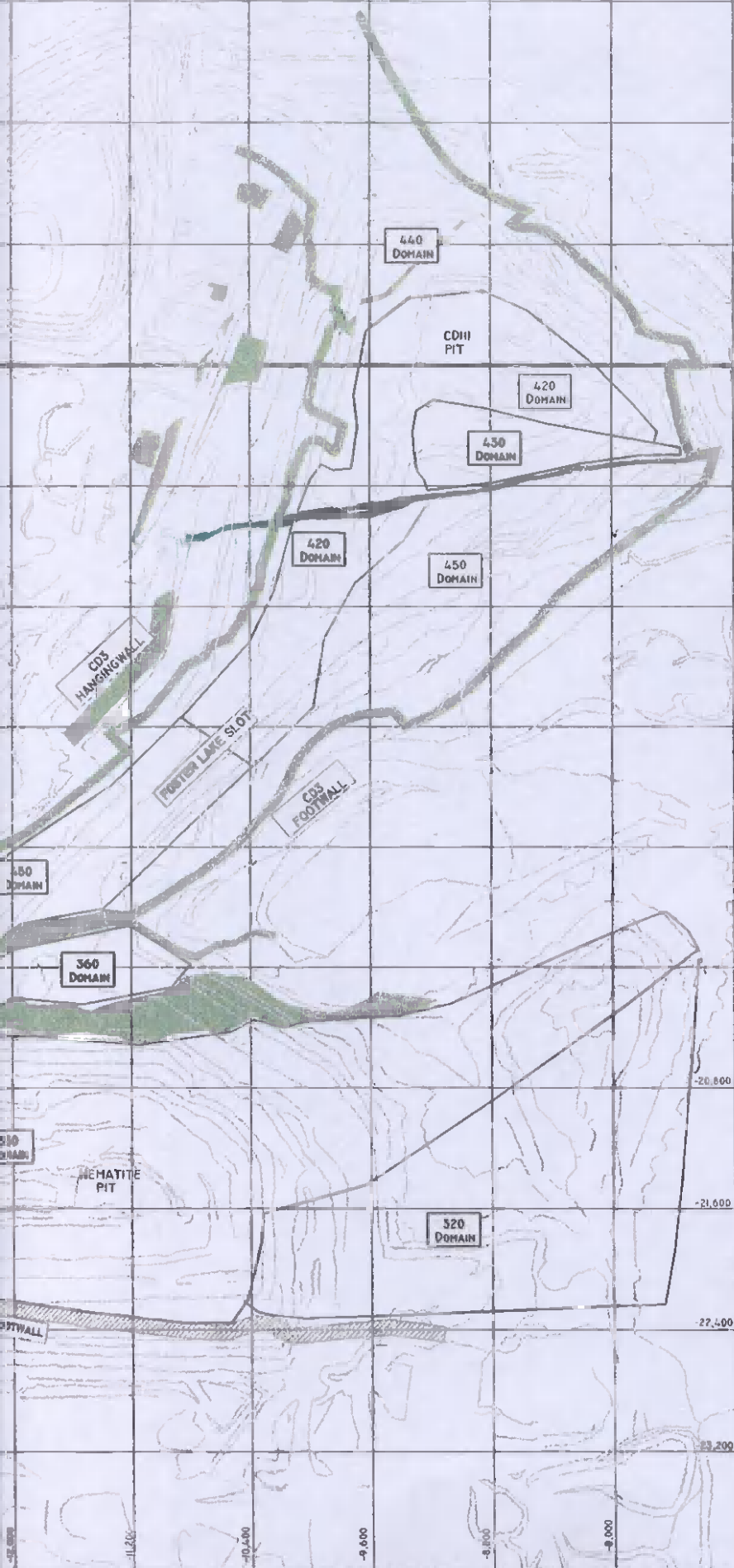
For the purpose of mine modeling, the deposit has been divided into geologic domains (Figures 1, 2 and 3; Table 1) based in part on lithology but, more importantly on the metallurgical response based on bench tests and in the processing plant (Table 2). The primary ore/waste parameters are weight recovery (the percentage of each ton of ore that is turned into concentrate and pellets; i.e. the value of that ton of ore) and grade (does the ore contain sufficient iron and silica grade). Other factors which can effect the plant operation and pellet quality are mineralogy (as related to total oxides and loss on ignition); trace chemical composition (in particular phosphorous but also Mn and alkalis); crude, magnetic and slime iron; and autogenous grinding feed. It should be noted that these data are essentially all based on rather involved bench tests that may not directly reflect the plant response.

Structural Geology

In this region, the Marquette Range Supergroup is in a narrow east west trending basin known as the Marquette Synclinorium. This basin lies along the Great Lakes Tectonic Zone as originally defined by Sims and others (1980) as a Late Archean crustal scale suture with Superior Province granite-greenstone terrain to the north and older Southern Complex gneiss to the south. The northern margin displays a more or less complete stratigraphic succession from the base of the Chocoy Group through to the top of the Menominee Group. The southern margin is truncated; the Negaunee Iron Formation at the top of the Menominee group abuts directly against the high grade Archean Gneiss. This sharp contact is marked by outcrops of the Palmer Gneiss, described as a "comminuted, sericitised and partly silicified phase of the lower Precambrian gneiss" (Van Hise and Bayley, 1897).

Mining activity since that time has exposed a large face (Stop2) of the chloritic schists that form part of the Palmer Gneiss. It displays mega-shear bands, the spacing between





MAGNETITE CD-III CROSS SECTION

TILDEN MINE Figure 1

DATE: 3/11/99

0 400 800 1000

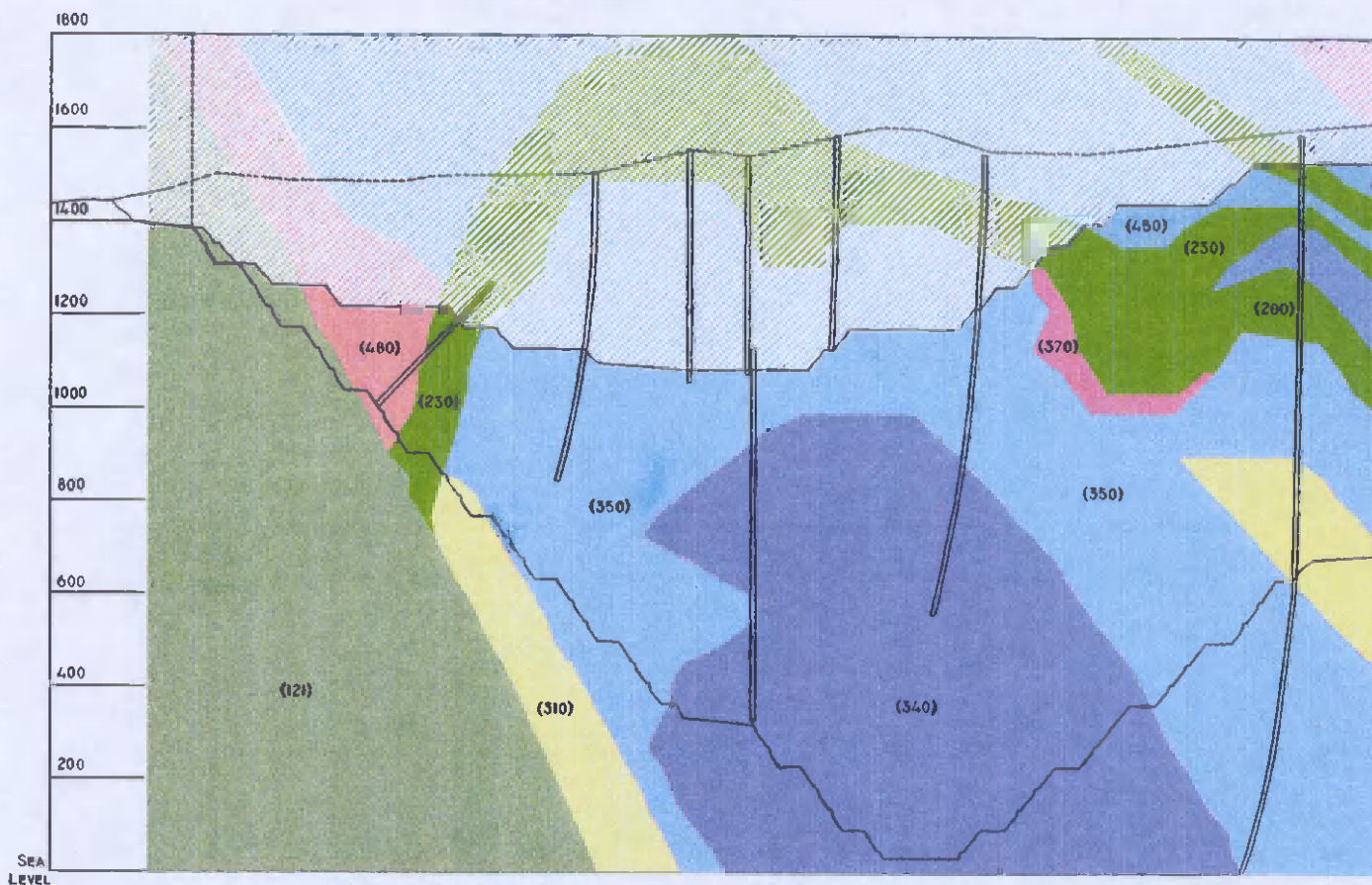
INTRUSIVE MP Footwall

Domain Boundaries

BENCH CREST AND TOE

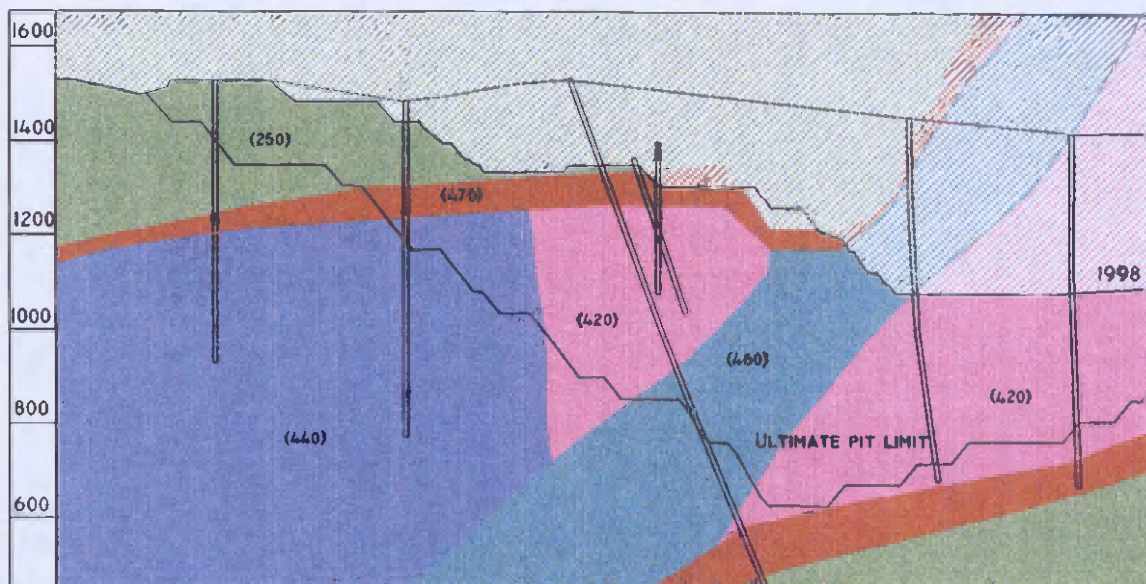
TILDEN HEMATITE

NORTH-SOUTH CROSS-SECTION -13,100



TILDEN MAGNETITE -

EAST-WEST CROSS-SECTION -16,000 WEST



PIT

LOOKING WEST

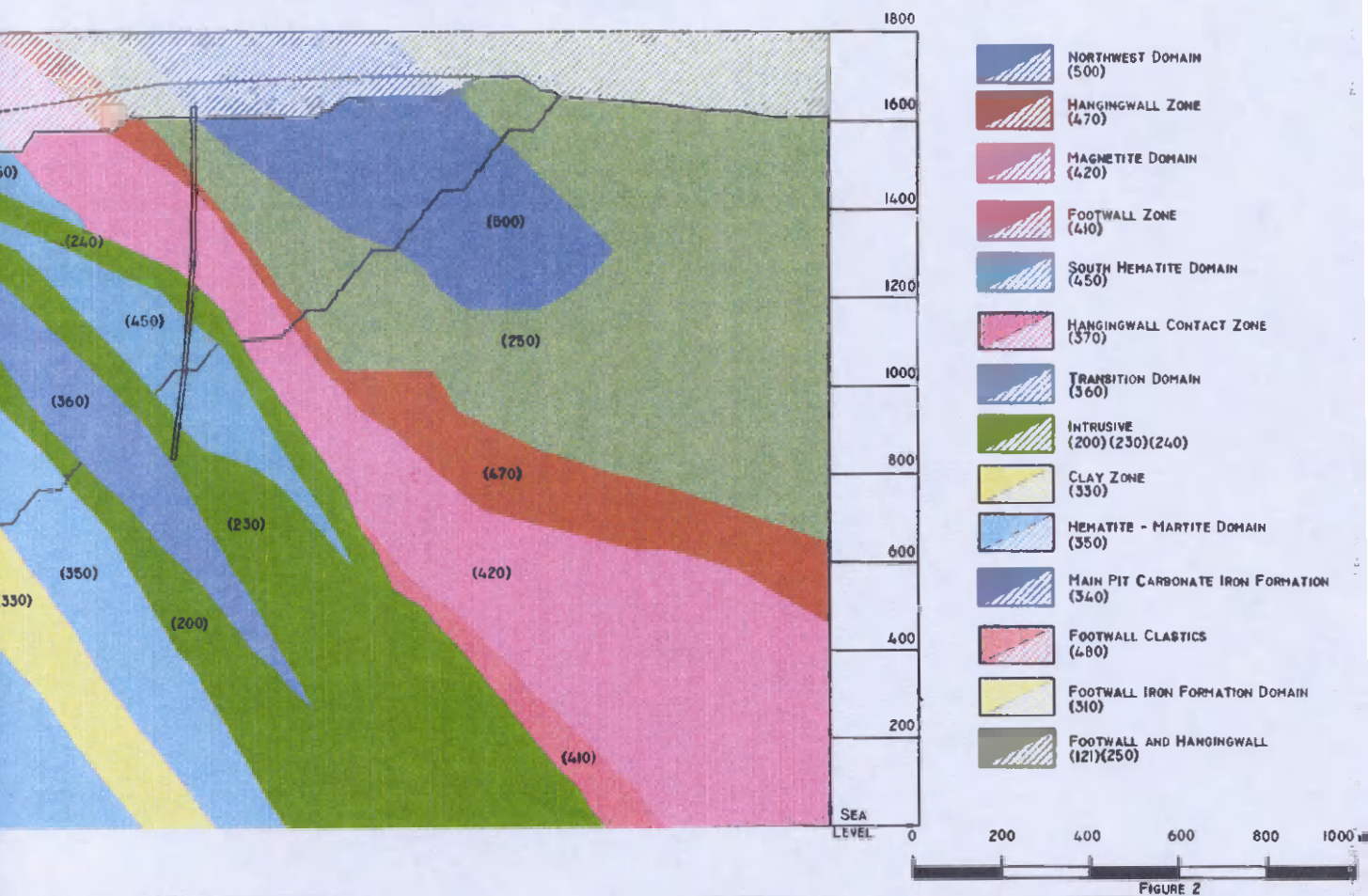


FIGURE 2

CDIII PIT

ST

LOOKING NORTH

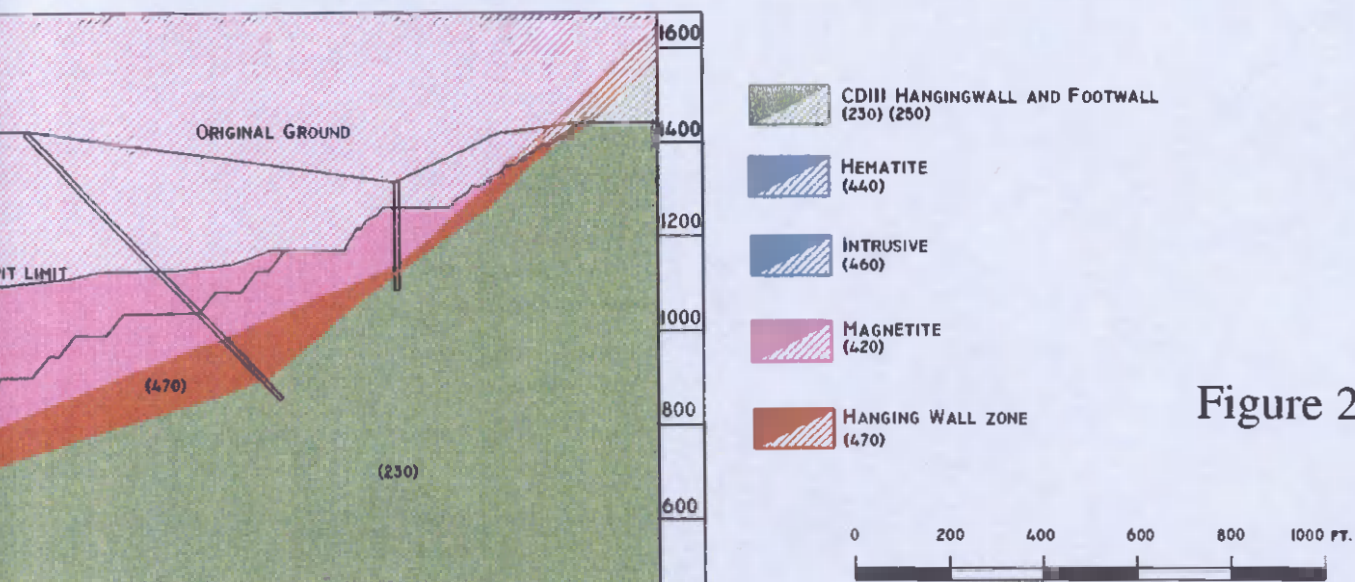
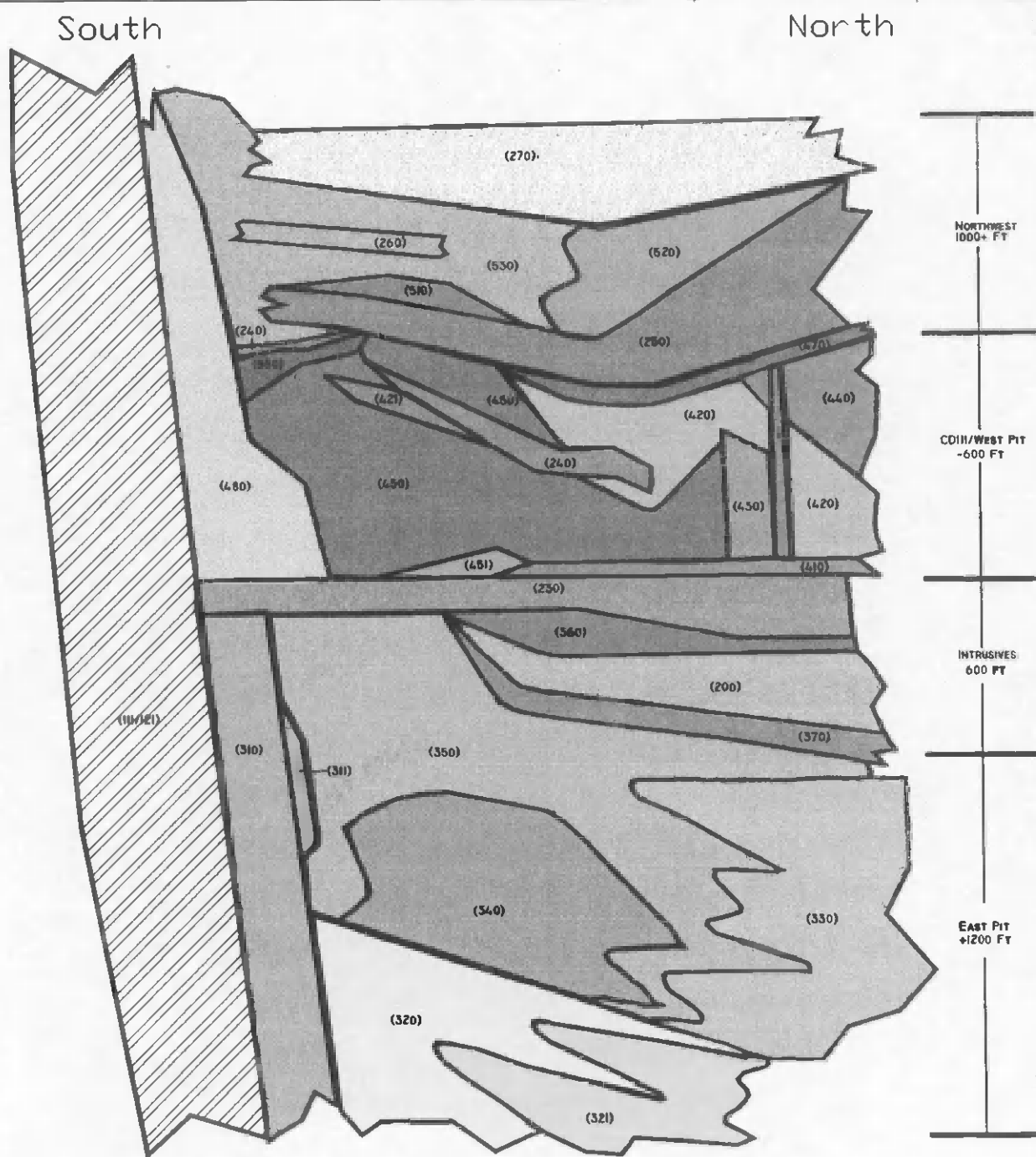


Figure 2

FIGURE 3



DIAGRAMATIC STRATIGRAPHIC SECTION OF TILDEN MINE
Looking West

Refer to table 1

Figure 3

Table 1: Geologic domains and subdomains at the Tilden Mine. The domains are based on lithology and metallurgical response. The numbers for each domain correspond to those shown on Figures 1, 2, and 3 and are used as drill core codes and in modeling of the deposit using MEDSYSTEM.

500 NORTHWEST DOMAIN

The Northwest Domain is stratigraphically above CD III/West pit hanging wall metadiabase (250) and below North Intrusive (270); this domain includes numerous dikes and one mappable igneous horizon, the West Intrusive (260).

550 **West Hematite domain**, restricted to the Far West Extension, is dominantly hematite chert with mixed goethite, recoveries around 40% and variable but elevated phosphorous. Contact with 530 domain is defined by a thin intrusive and metallurgical change.

530 **(Hematite)-Goethite domain** includes flot "ore" (531) and WIF (532).

531 Flot "ore" that is dominantly goethite-chert with weight recovery of iron in the low 30 to -mid 40 %; variable, but generally high silica and phosphorous.

532 WIF "ore" is oxidized martite/goethite; low weight recovery, high silica and phosphorous; low heads indicate original iron formation may have been carbonate(?).

Sulfates are locally common in bench faces.

520 **Magnetite domain** is dominantly magnetite-carbonate with silicate horizons. This may be flot and/or mag ore in part depending on liberation.

510 **Clastic horizon** is at the contact with top of the CDIII/West pit hanging wall (250) in a local (?) syncline. This horizon is in part flot ore.

400 CDIII-WEST PIT DOMAIN

This domain is stratigraphically between CDIII/West pit hanging wall metadiabase (250) and CDIII footwall (230). This domain includes numerous small dikes and sills, a Keweenaw dike and the West Pit Marker horizon (240).

480 **Footwall clastic zone** along Main pit footwall (100). Consists of dominant martite clastics with coarse quartzite/conglomerate and interbedded martite-hematite chert.

470 **Hanging wall zone** along base of CDIII/West pit hanging wall metadiabase (250). Defined as WIF due to very fine grain size and/or oxidization.

460 **Dike domain** is defined as a northeast trending zone of chloritic dikes and associated oxidized and unoxidized iron formation.

450 **South Hematite domain** occurs in the south part of CDIII and the West pit. It contains flot ore of variable metallurgy and WIF and is dominantly thin bedded, fine-grained hematite-martite chert although some zones may be oxidized carbonate.

451 **Goethite zones** within hematite domain. These zones are associated with folding and faulting. A goethite zone along the footwall is present but not broken out as a domain at this time.

452 **Goethite zone along CDIII footwall** south of Keweenaw dike. This zone typically has high slime Fe, may be oxidized Carbonate (430) domain along intersection of dike and footwall.

440 **North hematite domain** consists of fine grained oxidized martite-hematite chert with numerous dikes. The boundary between this domain and the Magnetite domain (420) trends northeast and dips steeply south. Flot ore in part.

430 **Carbonate domain** is carbonate flot ore with low magnetite content, high weight recovery and low concentrate grade. Fault bounded on north and south but apparently gradational down dip to the west into magnetite domain (420).

420 **Magnetite domain** consists of magnetite-carbonate and magnetite silicate-chert with variable oxidation and grain size. This domain has relatively sharp boundaries with other domains. Domain generally defined by magnetite content, not ore type, so it contains potential flot ore.

421 **West pit magnetite domain** is an isolated(?) zone of high grade magnetite in the west pit. It is defined by drilling and blast pattern data.

410 **Footwall zone** is defined as the magnetite-silicate horizon at the contact with the CDIII Footwall metadiabase (230). It is typically waste or low grade due to low magnetite content or poor liberation.

300 MAIN PIT DOMAIN

The Main Pit Domain contains iron formation units stratigraphically below the CDIII footwall metadiabase (230) and/or the East pit hanging wall metadiabase (200). This domain includes numerous small mafic intrusives.

370 **Hanging wall contact** includes zones of erratic metallurgy along the base of the CDIII footwall (230) or East pit hangingwall (200).

360 **Transition zone** between CDIII footwall (230) and East pit hanging wall (200). This zone consists of variably oxidized hematite iron formation and mafic intrusives. Restricted to north side of East pit.

350 **Hematite-martite domain** in East pit consists of various types of martite chert. This domain includes horizons of magnetite-carbonate iron formation and thin dikes. Gradational transition over 20-50 feet to Carbonate iron formation (340).

340 **Carbonate iron formation** is stratigraphically below the hematite-martite domain (350) in East pit. It consists of martite-carbonate-chert with variable magnetite/martite/Fe silicate content. This unit is defined by magnetic Fe, weight recovery and total oxides. It has lower weight recovery and higher concentrate grade than CDIII carbonates (430) and may be magnetite ore in part.

330 **Clay zone** is defined as the horizons of iron formation outlined as waste due to high silica from montmorillonite (or other) interference. This does not differentiate nonliberating hematite material. This zone may be stratigraphically controlled. Includes some flot ore within boundaries.

320 **East pit clastics** are mixed siliceous clastics and iron formation. This unit includes oxide and carbonate horizons. It may be the stratigraphic equivalent of carbonate domain (340) down plunge to the west (?).

321 **Clay zone in clastics** is similar to clay zone (330) but in clastic domain.

310 **Footwall iron formation domain** consists of variably oxidized oxide iron formation and coarse clastics. This domain is typified by erratic metallurgy.

311 **Earthy fines** are high grade (>50 weight recovery and >50 head Fe) oxidized zones are controlled by structures within the footwall domain.

200 INTRUSIVE DOMAINS

These domains are used for correlations of the iron formation domains, and structural trends. They appear to be conformable at the scale of the ore body. These rocks are generally interpreted as intrusives, they consist of mafic rocks which vary from diabasic to porphyritic to aphanitic. All horizons appear to thin to the west and south. Contacts tend to be sheared and locally oxidized. Contact metamorphism of the iron formation is minimal and, if present, results in finer grained iron formation. Synclinal structures and intersections with dikes have focused oxidation of the iron formation.

270 **North intrusive** is a poorly defined horizon at the top of the Northwest zone (500).

260 **West intrusive** is a poorly defined but mappable horizon within the Northwest zone (500).

250 **CDIII/West pit hanging wall** is a relatively easily mappable horizon and along with the CDIII footwall (230) is one of the principle horizons for stratigraphic correlations between the CDIII pit and the Main pit.

240 **West pit marker** is a thin but continuous horizon within the CDIII/West pit stratigraphy (300). It is interpreted to extend from the Foster Lake slot through the West pit.

230 **Top of the CDIII footwall** defines the base of the CDIII/West pit domain (400) while the base defines the top of the Main pit east domain (300).

220 **Chloritic and diabase dikes and thin sills** occur in all domains. This unit includes east-west trending 30+ foot thick Keweenawan dike in CDIII.

200 **East pit hanging wall** is separated from the CDIII footwall (230) by the Transition zone (360) iron formation. This unit occurs along the north side of the East pit, the base of this horizon marks the top of the Main pit East domain (300) for mining and planning purposes

100 MAIN PIT FOOTWALL DOMAIN

This domain consists of Archean metamorphic rocks which are separated from the iron formation domains by an east-west trending, north-dipping high angle fault.

121 **Chloritic schist** is the dominant footwall rock type exposed within the pit and in the drill holes. This rock may be the extension of the CDIII footwall horizon (230) within the fault zone.

111 **Granite gneiss** occurs south of the chloritic schist (121) but is only poorly exposed in the pit. This domain has not been used in the drill hole codes.

999 OVERBURDEN DOMAIN

This domain consists of Quaternary overburden, rock fill and broken bench material.

Table 2: Glossary of terms and abbreviations.

Natural Weight Recovery - The amount of material recovered from the material fed into the concentrator circuit. In other words, it's the tons of concentrate made (measured as filter cake) from tons of crude ore used (measured by #3 belt scale).

Metallurgical Weight Recovery (Met. Wt. Rec.) - Calculated by comparing the iron losses (as tailings) with the iron content of the crude ore fed into the concentrator circuit (i.e., the head Fe). The formula used for this calculation is called the iron balance formula, or sometimes called the concentration formula.

$$\text{Wt. Rec.} = \frac{(\text{Head Fe} - \text{Tail Fe})}{(\text{Grade} - \text{Tail Fe})} \times 100$$

Grade - Also called the concentrate grade, is a chemical measurement (assay) of the total iron oxide of the concentrate. Iron oxide is found in iron minerals such as hematite (Fe_2O_3), magnetite (Fe_3O_4), goethite ($\text{Fe}_2\text{O}_3 \cdot \text{OH}$), and iron carbonate (FeCO_3).

Concentrate Silica Grade - The chemical measurement (assay) of the % SiO_2 in the concentrate. When a lower concentrate silica grade is achieved, the losses in iron units (tailings) increases.

Head Grade - The assayed iron content of the crude ore fed into the concentrator circuit.

Iron Recovery (Fe Rec.) - A calculation of the efficiency of the concentrator's ability to recover the iron available. This is calculated by comparing the Met. Wt. Rec., at some iron grade, with the head Fe of the crude ore. For example,

$$\% \text{ Fe Rec.} = \frac{(\text{Met. Wt. Rec.} \times \text{Grade \% Fe})}{(\text{Head \% Fe})}$$

Percent Magnetic Iron Recovered (% Mag. Fe Rec.) - The calculation of the efficiency of recovering the magnetic iron that was in the feed (crude ore). The Met. Wt. Rec., at some iron grade, is compared with the magnetic potential (i.e. head) of the crude ore. For example,

$$\% \text{ Mag Fe Rec} = \frac{(\text{Met. Wt. Rec.} \times \text{Grade \% Fe})}{(\text{Head Mag \% Fe})}$$

Tailings - The product lost in the process. Tailings always includes iron, because iron is always associated with many other minerals (silica, phosphate, carbonate, etc.).

Flot (flotation) - Flot ores are the martite, hematite, goethite and carbonates that are treated by selective chemical processes to achieve Fe and silica grade. The final stage of the magnetite process is flotation to achieve target silica grade.

WIF (waste iron formation) - Iron formation that due to low weight recovery and/or high silica cannot be treated in the plant to produce economic concentrate. Rarely, phosphorous levels are too high to be treated.

Magnetic iron - The percent of the crude iron that is concentrated in the Davis Magnetic Tube Test (DMTT).

$$\% \text{MagFe} = \text{DMTT Wt. Rec.} \times \text{DMTT Grade}$$

The assumption is that all of this occurs as magnetite. However, in the Tilden ores an appreciable amount of hematite is up locked with the magnetite and is carried into the DMTT concentrate. This tends to over estimate the magnetic Fe content by 1-2% points and therefore the over estimate weight recovery.

Satmagan - The satmagan magnetic iron content is measured using susceptibility and is the actual magnetite content of the crude or concentrate.

Domain - The deposit is divided into volumes of rock with similar metallurgical response. These are usually stratigraphic horizons but may be fault bounded or nonconformable alteration/oxidation zones. The domains are the basis for the economic and planning models.

C/ structures is on the order of 2.5 meters, most commonly such structures are hand specimen to microscopic in scale. They indicate the presence of a large, reverse dip slip, ductile shear zone with a NNE to SSW transport direction. The fact that the Negaunee Iron Formation is thrust up on to the older Archean Gneiss indicates that there must have been prior local subsidence here to form the sedimentary basin, a classic basin inversion pattern (Gillchrist and others, 1987).

Folds measured with in the Negaunee Iron Formation have axial surfaces and hinge lines that trend east-west to WNW, indicating a similar strain environment to that determined from the shear zone. The folding and shearing are thought to have occurred at the same time.

The iron formation is mostly a chemical or biochemical deposit. The clastic lenses that occur in the formation are thickest and most numerous in the south, thinning and becoming less frequent to the north (Breithart, 1983). The pattern suggests an asymmetric rift basin with a breakaway fault on the southern margin and a rollover on the north side. The principal source of clastic sediments would have been derived from the southern margin that was being uplifted along the fault. This episode is related to the development of a passive margin during the early Proterozoic. Subsequent compression during the Penokean Orogeny inverted the basin and initiated reverse faulting that gave rise to the shear zone (Cambray, 1978). To the east, in the Harvey Quarry, a similar pattern of younger over older thrusting is observed suggesting that this relationship is common along the Synclinorium and confirms the early rift and later thrusting pattern.

Mining

Ore reserve and long range mine planning is done in MEDSYSTEM using 50'x50'x45' blocks based primarily on development drill holes which are on a nominal 300 foot spacing. Weekly plans and daily ore predictions are based on blast pattern samples, which are on about 90 foot centers. Reconciliation of ore, waste and pellet production between the "model" and actual production shows less than 1% difference.

The annual mining task is to move approximately 38 million long tons, about 20 million long tons of ore and 18 million long tons of stripping waste, to produce 7.8 million long tons of flux pellets per year. Production since 1974 has been 126 million long tons of pellets from 355 million long tons of ore at a stripping ratio of 0.94. As of January 1, 1999, the proven and probable long range (30 year) mine plan reserve was 628 million long tons of ore containing 233 million long tons of pellets at a stripping ratio of 0.77.

The loading fleet consists of two P&H 2800 (38 cubic yard) cable shovels, three P&H 2100 (17cubic yard) cable shovels and two 994 (21 cubic yard) Caterpillar wheel loaders. The hauling fleet consists of three 793 (240 ton) Caterpillar trucks, seven 789 (190 ton) Caterpillar trucks and six Haulpack 630E (170 ton) trucks. Drilling is done with one P&H and one GD 120 drill.

Field Trip Stops

The actual stops to be visited and their locations cannot be determined until just prior to the field trip. The generic stop descriptions are provided in this guide and the actual localities to be visited will be provided to participants on the day of the field trip.

Stop 1 - Pit Service Building

Before beginning the tour of the Tilden pit, the mine safety rules will be reviewed and a short video of the Tilden Mine operation will be shown. The video, not particularly geologic, describes the mining cycle, milling and pelletizing processes that have a major impact on the ore quality determinations.

Stop 2 - Main Pit Footwall Shear Zone

Chlorite schist defines the footwall of the Tilden ore body. This chlorite schist is described in the literature (Van Hise and Bayley, 1897; Gair, 1975) as part of the Palmer Gneiss and marks the boundary between the Archean Compeau Creek gneiss of the Southern complex and the early Proterozoic sediments. This contact extends for approximately seven miles east from the Tilden Mine. Gair and Simmons (1968) made a complete study of this rock and proposed three possible modes of origin: 1) alteration and shearing of Precambrian rock during faulting; 2) migration of fluids along the contact between lower and middle Precambrian rocks; and 3) alteration of a regolith during folding. At the Tilden Mine, there appear to be two varieties of gneiss, a southern sericitic phase related to a granitic protolith and a northern chloritic phase with a diabasic protolith.

At this locality one can see the dominant, steep north dipping S surface cut by the more gently north dipping C/ surface (Figure 4). The intersection between the S and C/ plunges gently to the WNW. The movement plane on the shear zone is at right angles to this intersection and the intersection of this plane and the boundary of the shear zone (determined from drill records) gives the direction of movement (marked with a filled triangle on Figure 5). The pattern of the S surfaces and shear bands give the sense of movement (Figure 4). Chemical analyses indicate that the protolith for the shear zone was most likely to have been one of the diabase bodies found interlayered with the banded iron formation.

The steep north dipping (~60°) foliation in the chlorite schist creates a bench and slope stability concern. This is controlled by triple benching to a 45° final wall slope with 35 foot catchers. Proper clean up along the toe line is critical to avoid "undercutting" the foliation.

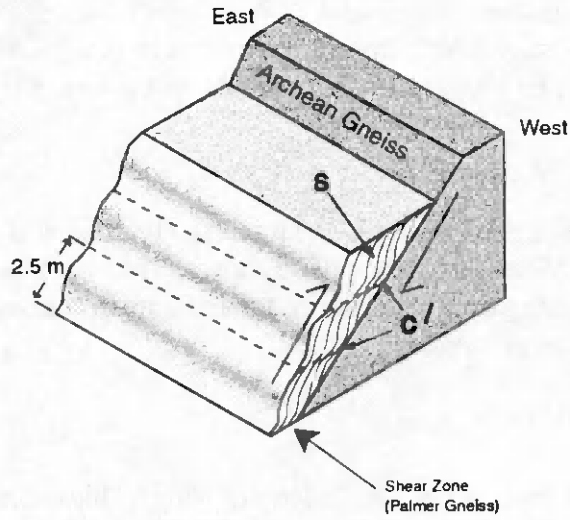


Figure 4: Footwall shear zone, Tilden Mine.

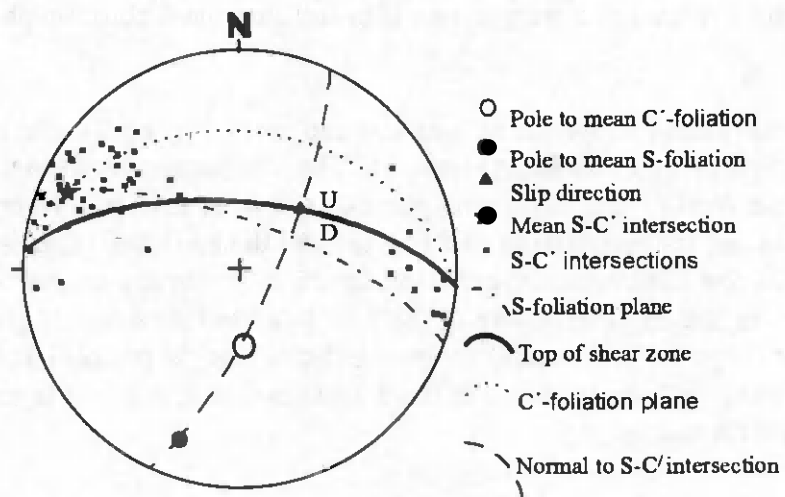


Figure 5: Stereo projection of shear zone structures.

Stop 3 - Martite and Main Pit Carbonate Domains

The Martite and main pit Carbonate domains lie stratigraphically below the CDIII Footwall and Main Pit Hangingwall intrusives. This is metallurgically "good ore" and is typically characterized by high weight recovery (35-45+%), low phosphorous, low slime iron and good grinding media. With crude Fe around 35%, iron recovery averages over 70%. The 'best' ore is centered on the Main Pit anticline and consists of thick bedded (2-4 cm) chert with variable martite and magnetite plus subordinate carbonates and silicates. The boundary between the Martite and Carbonate domains is based on higher magnetite content; the Carbonate domain contains low calculated total oxides that may be due to iron silicates. The variation in magnetite content may reflect either the environment of deposition or diagenesis; it is unlikely to be due to supergene effects.

This domain comprises about 56% of the ore reserve. The mine plan attempts to control the blend percentages to about 50% of this domain. This has been only partially successful due to pellet quality concerns when blending with other types of ore. The planned final depth of the Main pit is about sea level so the pit will be about 1000 feet deeper.

As the base of the iron formation is not exposed at the Tilden Mine, the stratigraphic thickness is unknown. The thickness exceeds 1000 feet and is probably underlain by and is gradational into undifferentiated clastics and iron formation of the Empire Mine.

Stop 4 - Mafic "Intrusive" Igneous Horizons

Due to the lack of clear stratigraphic markers within the iron formation and the rapid facies changes in the iron formation, several igneous horizons are used for stratigraphic and structural correlation (Figure 1).

The term 'intrusive' or 'dike' is used for green and gray-green mafic igneous rocks, which vary from (semi) conformable sill-like horizons to obviously crosscutting bodies. Since the fabric varies from diabasic to porphyritic to aphanitic, the conformable bodies are usually interpreted as synsedimentary sills but may be flows. The sills range in thickness from a few tens of feet to at least 600 feet with the thicker horizons thinning to the south. Dikes, obviously crosscutting bodies, are typically 5 to 20 feet thick. The dikes may be feeders. The dikes and thinner parts of the sills are commonly altered to chlorite and carbonate while the thicker parts retain primary igneous textures. Contacts with the iron formation are variably sheared and altered.

The principal sills are the Main pit hangingwall, CDIII footwall and the CDIII hangingwall. The sills and majority of the dikes appear to be of early Proterozoic age but, there are several dikes that are interpreted to be of Keweenawan age based on the magnetic signature. Dikes commonly fill faults and fracture zones. The igneous event that emplaced the sills and majority of the dikes may be related to the Clarksburg, Hemlock and Emperor Volcanics.

Dilution from dikes, especially along shallowly dipping contacts, is the most common type of internal waste. Incipient recrystallization due to contact metamorphism and quartz overgrowing magnetite results in high silica waste along the CDIII hangingwall.

Stop 5 - West Pit/CDIII Hematite Domain

The West Pit/CDIII Hematite domain in the west pit is stratigraphically between the CDIII hangingwall and footwall. This domain extends from CDIII along the north limb and over the crest of the Main pit anticline. In contrast to the martite domain, this is metallurgically 'poor' ore with higher slime iron, phosphorous and poor grinding. Although weight recoveries are relatively good (about 36% Fe), due to the high crude Fe of 40%, the iron in this domain is below 60%. Mineralogically and texturally, this domain differs from the martite domain in being dominantly platy hematite with thin (mm scale) chert laminae. Presumably, the bedding thickness reflects the original sedimentary features but it is unclear as to the nature of the oxidation event that produced the hematite (related to deposition, diagenesis or supergene alteration).

With a thickness of about 600 feet, this domain contains 27% of the ore reserve but, due to blending concerns for phosphorous, slimes or grinding, it is often difficult to maintain that percentage in the blend going into the processing plant.

Stop 6 - Magnetite Domain

The Magnetite domain is the stratigraphically equivalent of the West Pit/CDIII hematite but is essentially restricted to the CDIII syncline (basin?). Magnetite ore quality is determined by the percentage of the crude iron that occurs as magnetic iron (magnetic concentrate determined by the Davis Magnetic Tube Test). On average, the Magnetite domain contains 27% magnetic iron with 37% total crude iron. With about 90% magnetic iron recovery in the plant, weight recoveries are 34-36% iron. Mineralogically, the ore consists primarily of magnetite-siderite-chert with variable hematite and silicates. This mineralogy, along with the thin laminations, appears to indicate a restricted basin and a reduced environment of deposition.

There is some scientific controversy as to the role of diagenesis with respect to the relationship between magnetite, hematite and siderite. Within the Magnetite domain there is a fault/dike-bounded zone of low magnetite siderite ore; it is uncertain whether this is the protolith of the magnetite ore. The southern extension of the CDIII magnetite into the hematite domain contains the highest grades (~30 magnetic iron). The sharp contact, not structural, indicates that this is some sort of redox front but it is unknown whether it is of diagenetic or supergene origin.

Approximately 23% of the Tilden ore reserves are in magnetite. Development of the reserve involves a series of pushbacks along the west wall in the intrusive. The wall is planned to move back about 800 feet and the pit is to be deepened about 600 feet.

Acknowledgments

We thank Bill Cambray and Cheryl Webster for their contribution of the Structural Geology section in the Introduction and structural discussion in Stop 2.

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Geologic Field Trip to the Empire Mine

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Introduction

The Empire mine commenced operations in 1963; over the past thirty-five years the operation has produced nearly 200 million long tons of pelletized iron concentrates. The Empire Mine represents a partnership of steel making and iron mining interests and is partially owned and operated by the Cleveland-Cliffs Iron Company. The reserve is about 600 million long tons of magnetite ore. The current annual production is 8.4 million long tons of pellets from 27.5 million long tons of ore. Han (1975) provides a detailed description of the Negaunee Iron Formation at the Empire Mine.

Stratigraphic relationships within the Negaunee Iron Formation in the vicinity of the Empire Mine are:

- Upper Undifferentiated Series (+ 1500'): intermixed sequence of carbonate, silicate, clastic and "lean" carbonate assemblages.
- Clastic horizon (200-300'); graywacke and feldspathic quartzite interbedded with chert, iron carbonate minerals and magnetite.
- Carbonate horizon (350-500'): alternating bands of magnetite-chert and chert, with siderite or ankerite distributed throughout. Local, minor beds of riebeckite and aegerine-augite are present near the upper contact.
- Silicate horizon (400-500'): alternating laminae of magnetite, carbonate, greenish micro- to sub-microscopic iron silicate minerals (principally stilpnomelane), and chert.
- Lower Undifferentiated Series (700-1500'): intermixed sequence of carbonate, silicate minerals and clastics (clastics increase toward base of interval).

The basal contact of the Lower Series is transitional with the underlying Siamo Slate. The Siamo Slate is represented in the mine area by quartz-arkose and graywacke.

A geologic map and section of the Empire Mine (Figure 1 and 2) illustrate the relationships between the various lithologic units.

Iron formation at the Empire Mine is transected by a number of near-vertical, chloritized metadiabase dikes. The dikes occupy faults, believed to be of early Proterozoic age, which are probably related to basin development. The dikes have had a significant localized impact on ore processes. The fine grain size of magnetite (5 μ) in iron formation adjacent to the dikes represents a "selvage" which was apparently impervious to subsequent processes that influenced growth of the magnetite grains in other portions of the iron formation. Effective liberation of magnetite in these "fine-grained" rocks can rarely be achieved.

The iron content of the iron formation at the Empire mine is fairly uniform, about 32-35%. The amount and grain-size of magnetite determines ore quality. Ore-forming processes contributed and remobilized iron by diagenetic or low-grade metamorphic reactions of recrystallization and replacement. Oxidation of siderite has resulted in large-scale replacement by magnetite, but



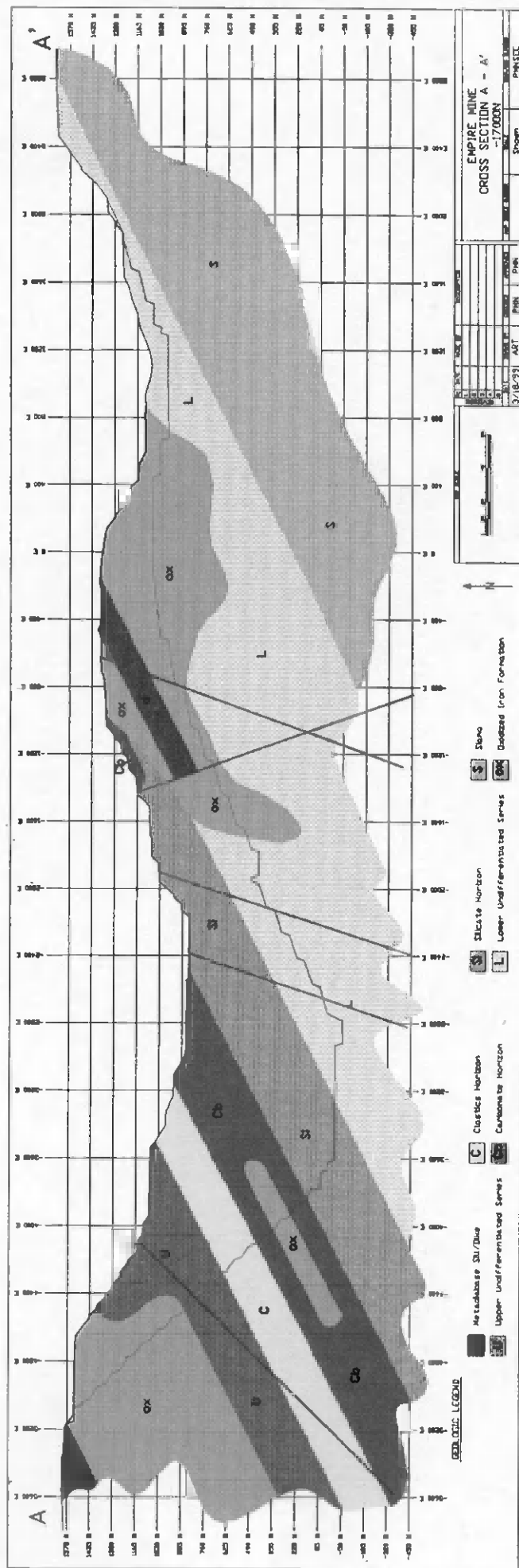


Figure 2

chert layers are also replaced by magnetite; the grain size of the magnetite in these enriched zones is coarser than magnetite in zones not effected by replacement.

Secondary oxidation has a profound impact on ore quality at the Empire Mine. Non- or weakly magnetic iron minerals (e.g., martite, hematite) characteristic of oxidized zones are typically rejected during primary magnetic separation. Incipient or partial oxidation of magnetite grains may cause them also to be rejected, if not in magnetic separation, then in flotation stages. However, it is often difficult to recognize the extent of oxidation and predict its impact on plant recovery. The oxidation is thought to be largely, if not entirely, the result of supergene processes. Circulation of the oxidizing fluids was controlled by faults, dike contacts and clastic beds and lenses. However, the boundaries of oxidized zones are very irregular and difficult to define.

Due to the very fine grain size of magnetite in virtually all Empire iron ores, including the carbonate ores, extremely fine grinding (93-95% passing 500 mesh) is required to achieve sufficient liberation of magnetite for product specifications. Process control is dominated by the specification for SiO_2 in the final product. Smaller average grain size of magnetite in silicate-type ores means that they must be ground finer to achieve acceptable liberation. In general, the finer grain size also implies increased work index so that grinding becomes significantly more costly.

Field Trip Stops

The actual stops to be visited and their locations cannot be determined until just prior to the field trip. The generic stop descriptions are provided in this guide and the actual localities to be visited will be provided to participants on the day of the field trip.

Stop 1 - Dispatch Overlook

Mining development at Empire has focused on the Main pit, with significant contributions from satellite pits to the north (CD-I), east (Section 20) and west (Southwest Extension), and expanding development to the northwest (CD-V). The bottom bench of the Main pit is approximately 1,000 feet below the dispatch overlook, and the pit will ultimately be developed 750 feet below the present mining level.

The bottom bench of the Main pit is developed almost entirely in the Carbonate and Silicate horizons. The iron formation in this area strikes about N35°E and dips 30-35° to the northwest.

Stop 2 - First Class Carbonate

The Carbonate unit is gray to dark gray, relatively coarse-grained (magnetite grain size: 20-30 μ) and characterized by "thick" (5-25 mm), indistinct magnetite-rich and chert-rich layers with subordinate siderite and ankerite. The term "carbonate" is utilized at the Empire Mine to indicate soft ores (work index < 10) with very good liberation characteristics (low concentrate of SiO_2). These high-grade ores have been the "life-blood" of Empire's production.

Stop 3 - First Class Silicate

Silicate iron formation consists of thin laminae (2 mm) of magnetite (minor to very minor amounts of silicate, carbonate, chert, and clastics) and greenish or brownish-gray mixtures of silicate minerals, siderite, magnetite, chert and clastics. The silicate minerals are dominantly stilpnomelane and minnesotaite. The Silicate horizon commonly has a greater abundance of carbonate minerals than the Carbonate zone. The grain size of the magnetite (5-20 μ) is finer than in the Carbonate-type. The term "silicate" at the Empire Mine is applied to ores with work index > 10 and liberation characteristics that are inferior to carbonate ores; silicate or yield higher concentrate of SiO_2 .

Stop 4 - CD-V

Future development of the mine will be principally focused in two areas: the "pillar" between the Main pit and the Section 20 pit (west wall), and the north and northwest areas of the Main pit termed CD-V. Development of the west wall includes relocation of the existing rail lines around the east side of the Section 20 pit; the "pillar" area will then be excavated to expose ores in the wall and, more importantly, below the bottom of the present pit.

The CD-V pit is being developed in the Upper Series horizon, characterized principally by carbonate-type ores and clastic bands and lenses. Much of the yellowish carbonate material contains very little magnetite ("lean" carbonate), consisting dominantly of siderite and chert. However, very rich carbonate ores are also present in the push-back of the Main pit wall.

Current development is just below a large diabase sill that is 200-400 feet thick. Several of these large, generally conformable, tabular diabase bodies intrude the Negaunee Iron Formation in this area of the mine. Predictably, "fine-grained" effects are extensive adjacent to these large igneous bodies.

In the CD-V area of the mine, iron formation and interlayered sills have been folded into several small- to moderate-scale anticlinal and synclinal features. Fold axes plunge 10-20° toward the northwest.

Bounding CD-V to the north is a large area underlain by magnetite-bearing iron formation that, because of its extreme hardness (work index 18-20) and poor liberating qualities, is presently regarded as a resource, not a reserve. The nature of the metallurgical problems in processing these ores is under investigation by Cleveland Cliffs' research group.

Stop 5 - CD-I

CD-I has been an important source of very high quality (high weight recovery, low concentrate SiO_2) carbonate material for blending with lower quality ores from other locations in the mine. Iron formation in CD-I strikes north-south and dips about 30° to the west. Two Keweenawan age (1.1 Ga) diabase dikes cross the pit in a westerly to southwesterly direction. These two dikes are coarser-grained and fresher in appearance than the other, older early Proterozoic diabase dikes.

The current phase of pit development in CD-I will be completed in 1999. High quality carbonate ore extends to the west beneath the pit wall but its potential development is hindered by the large amount of stripping required. About 750 feet of overlying waste rock would have to be mined in order to access the ore.

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Field Trip 4

**Paleozoic and Glacial Geology from Au Train to
Grand Marais, Michigan**

Leaders: R.S. Regis and J. Anderton

PALEOZOIC THROUGH RECENT



Donald G. Cliney, Director

R. Thomas: *Geog. & State Geologist and Chief*

GEOLOGIC NAMES COMMITTEE

INFORMAL TERMS

STRATIGRAPHIC POSITION	INFORMAL TERMS	DAYS
Glacial Drift		_____ Cms

Base of sandstones at
Sagehen fm. _____ from sandstone

in lower part of

Michigan _____ {
 one - drop of _____ test
 Wday dist _____
 W day M _____ Cost & Chd

Marshall Sh _____ Gcs & Cd
Coldwater Sh _____ Coldwater lens
 |
 +--- sand ---+ Gcs

In upper part of
Bilwath Sh _____ "Bones" Western Highway _____ Old & New

Approx Sta _____ from and to _____ Ch & Co
Approx Bay La _____ Square Rev _____ Ch & Co

Upper part of _____ { Tapered Symptom
Tribune Group in _____ { Tapered Symptom _____ Old & Gen

Western Michigan _____ CH & Gen
Rogers, City La _____ CH & Gen

Durden La _____ Oil & Gas

Durden La [M] Upper _____ Oil & Gas

part of LARRY FOR (P) _____ Road City State _____ Zip + City

In last fm _____

Amendment No. _____ dated _____

Part of Sales _____ I have _____
Group of Users _____ or Range from _____ to _____

Concrete in _____ 4.2 distance _____ Gal
 Minimum thickness _____ 4.2 top _____

A-1 Carbonate _____ A-1 Silicate _____ Oil & Gas _____

Upper part of
Magerit Series ————— } Upper Magerit } ————— On & Co.

Lower Niagara Series _____, Clinton _____, Gen _____

Transfer Group _____ CH & S

Black River Group _____

Pratt & Whitney Group _____ of & _____

EXPLANATION

EXPLANATION

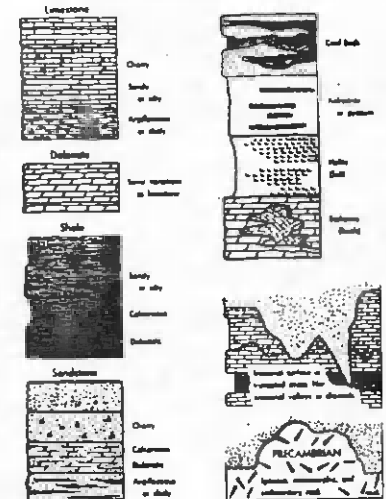
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CHART 1

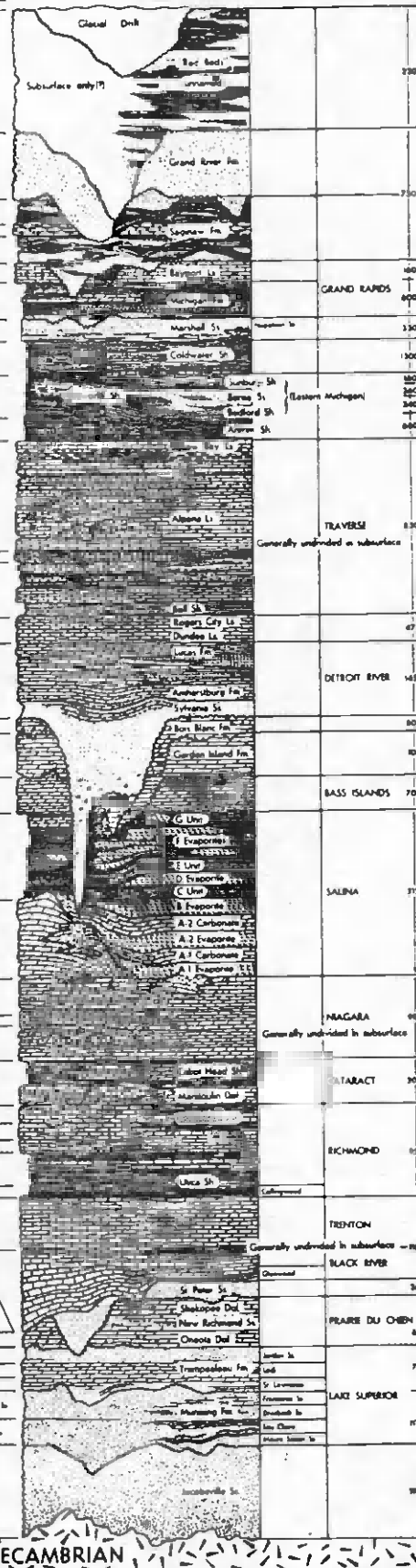
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PLEISTOCENE NOMENCLATURE									
ERA		SYSTEM		SERIES		STAGE			
CENOZOIC		QUATERNARY		RECENT					
				PLEISTOCENE					
					Wisconsin				
					Glaciation				
				Valley Stages					
				Two Glacials Interstadial					
				Marquette Stages (H. Huron)					
				Cory Stages					
				Terminal Stages					
				Langamian Inter-glaciation					
				Bismarck Glaciation					
OUTCROP NOMENCLATURE									
GEOLOGIC TIME		TIME-STRATIGRAPHIC			ROCK-STRATIGRAPHIC				
ERA	PERIOD	EPOCH	SYSTEM	SERIES	GROUP	FORMATION	MEMBER		
MESOZOIC	JURASSIC	LATE	JURASSIC	KIMBERIDGIAN					
				CONEMAUGH		Grand River Fm.		Worm Lake and associated sandstones	
	PENNSYLVANIAN	LATE	PENNSYLVANIAN	POTTSVILLE		Sagamon Fm.		Worm Lk.	
				MERAMECIAN	GRAND RAPIDS	Bayport Ls.			
	MISSISSIPPIAN	EARLY	MISSISSIPPIAN	OSAGIAN		Marshall Sh.		"Huronian" Ls.	
				KINDERHOOKIAN		Caldwaller Sh.			
	MISSISSIPPIAN-DEVONIAN				Unassigned				
	PALEOZOIC	DEVONIAN	LATE	DEVONIAN	CHAUTAUQUAN		Elworth Sh.		
					SENECAN		Marathon Sh.		
		DEVONIAN	MIDDLE	DEVONIAN	ERIAN			Sagamon Bay Ls.	
							Thunder Bay Ls.		
							Parker Farm Fm.		
							Norman Point Fm.		
							Four Mile Dam Fm.		
							Algonia Ls.		
							Huronian Gravel Ls.		
							Canabara Fm.		
						Fulton Point Fm.			
						Blackburn Quarry Ls.			
PALEOZOIC	EARLY	DEVONIAN	ULSTERIAN			Bull Sh.			
						Logan City Ls.			
						Dundas Ls.			
						Anderson Fm.			
						Lucas Fm.			
						Amherstburg Fm.			
						Sylvania Sh.			
						Box Bluff Fm.			
						Gardens Island Fm.			
						Basin River Dol.			
PALEOZOIC	LATE	DEVONIAN	CAYUGAN			St. Ignace Dol.			
PALEOZOIC	SILURIAN	MIDDLE	SILURIAN	NIAGARAN			Engadina Dol.		
	SILURIAN	EARLY	SILURIAN	MANISTIQUE		Candell Dol.			
				BURNT BLUFF		Schockcraft Dol.			
	SILURIAN	EARLY	SILURIAN			Hammonds Dol.			
						Byron Dol.			
	SILURIAN	EARLY	SILURIAN			Lima Island Dol.			
						Calder Head Sh.			
	PALEOZOIC	ORDOVICIAN	MIDDLE	ORDOVICIAN	ALEXANDRIAN	CATABACT	Marmoulin Dol.		
ORDOVICIAN		EARLY	ORDOVICIAN	CINCINNATIAN	RICHMOND	Big Hill Fm.			
							Sturgeon Fm.		
ORDOVICIAN		EARLY	ORDOVICIAN	CINCINNATIAN	RICHMOND	Bill's Creek Sh.			
PALEOZOIC		ORDOVICIAN	MIDDLE	ORDOVICIAN	MONAWYKIAN	TRENTON	Grass Quarry Fm.		
								Chandler Falls Fm.	
		ORDOVICIAN	EARLY	ORDOVICIAN	MONAWYKIAN	BLACK RIVER	Berry Falls Fm.		
	ORDOVICIAN	EARLY	ORDOVICIAN	CHAZYAN					
	PALEOZOIC	CANADIAN	EARLY	CANADIAN	PEABIE DU CHEN		Oronto Dol.		
		CANADIAN	EARLY	CANADIAN	ST. CROIXAN	LAKE SUPERIOR	Trumpeau Fm.		
CANADIAN		EARLY	CANADIAN	ST. CROIXAN	LAKE SUPERIOR	Amherstburg Fm.			
CANADIAN		EARLY	CANADIAN	ST. CROIXAN	LAKE SUPERIOR				
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CANADIAN	EARLY	CANADIAN	ST. CROIXAN	LAKE SUPERIOR					
CANADIAN	EARLY	CANADIAN	ST. CROIXAN	LAKE SUPERIOR					
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CANADIAN	EARLY	CANADIAN	ST. CROIXAN	LAKE SUPERIOR					
CANADIAN									

ROCK-STRATIGRAPHIC		
UNIT	MEMBER	GROUP
maximum thickness, in feet, of rock unit scale NO SCALE		

DOMINANT LITHOLOGY



PRECAMBRIAN

1999 ILSG Field Trip # 4 - Paleozoic and Pleistocene Geology from Au Train to Grand Marais, Michigan

Road log

Overview	-	Profile of Au Train channel	US41 S. (view to east at 2.3-3 mi.) continue 16.2 mi to M94, E. then 18.2 mi. to Forest Lk. Rd.
Stop 1	-	Au Train Falls	Return to Forest Lk. Rd. N 7.4 mi. to M28
Stop 2	-	Beach ridges and Au Train-Whitefish Channel	
Stop 3	-	Grand Island Overlook	M28 E. 2.5 mi. to H58, then to Washington St. (1.2 mi.), to Munising Falls (0.55 mi.)
Stop 4	-	Munising Falls	Return to H58 (0.55 mi.), E to Miners Castle Rd (3.7 mi.), then N to Miners Castle (4.9 mi.)
Stop 5	-	Miners Castle	Return to H58, continue E to Bear Trap Inn 9 (3.6 mi.), keep left and continue on H58 (end of pavement another 4.3 mi.) to Kingston Corner (11.2 mi. beyond pavement end)
Stop 6	-	Kingston Outwash Plains	N on H58 to 2-track on left (7.1 mi.) Proceed on 2 track 0.1 mi. & park Walk due W 400 yds (strenuous)
Stop 7	-	Turtle Lake Kettle	Return to H58, 2.1 mi. to dropoff into channel, @ 6.7 mi. is edge of upper outwash terrace, @ 8.7 mi. turn left on Log Slide Rd.. Continue to Log Slide (0.75 mi.)
Break		Picnic area @ NW side Grand Sable Lk.	
Stop 8	-	Log Slide	Return to H58. E on H58 to parking lot for Sable Creek falls and Ghost forest (5.6 mi.).
Stop 9	-	Ghost Forest	
Stop 10	-	Sable Falls	To Grand Marais (1.7 mi.)
Stop 11	-	Grand Marais Harbor Nipissing Bluff	
Stop 12	-	E-W channels crossed by M77	M77 to M28 (22.6 mi.) To Munising (22.4 mi.) To Marquette (44 mi.)

Detailed Road Log:

Overview of Au Train Whitefish Channel

From the Washington/Baraga St. intersection in downtown Marquette travel S on Baraga St (turns into US41). Along U.S. 41 at about 2-3 miles south of Marquette, a view to the east reveals a profile of channel cut by proglacial meltwater that flowed eastward along the margin of the Marquette (Grand Marais) ice. The feature was referred to by Hughes (1971) as the Onota outlier. Water spilled into the Au Train Whitefish channel southward to (present) Lake Michigan after passing through this channel. Continue on U.S. 41 south 16.2 miles to M94, turn east. Travel to 29.9 mi. to Chatham, turn S at stop sign, travel to 30.9 mi and turn E on M94, continue to 34.4 mi and turn N on Forest Lake Rd., travel 0.1 mi to dirt road on right, follow to gated parking area. Walk to falls.

Au Train Formation and Au Train-Whitefish Channel, Beach ridge complex

Return to Forest Lake Rd., turn N. Follow Forest Lake Rd. At 6.3 miles and all the way to M28, note the beach ridge complex. Turn E on M28 and travel to the Grand Island overlook parking lot on the N side of M28.

Grand Island Overlook

From the Grand Island overlook, return to M-28 and travel east 2.5 miles to Munising. Turn on H-58 after passing the Holiday gas station on the left (the Dogpatch restaurant is on the right at the intersection...excellent vittles! In a rustic, Li'l Abner setting). Continue on H-58 an additional 0.55 miles to Washington St., turn left and proceed to Munising Falls visitors center parking lot (0.3 miles).

Munising Falls

Return to H-58 from the parking lot and proceed north 3.7 miles to Miners Castle Road. Turn left. Travel 4.9 miles to the Miners Castle parking lot.

Miners Castle

Return to H-58 (4.9 miles) and turn east (left). Travel 5.9 miles to the Bear Trap Inn, veer left to stay on H-58. End of pavement 4.4 miles from the Bear Trap Inn. Continue to Kingston Corner junction (11.2 miles).

Kingston Plain

Travel north on H-58 7.1 miles to the small 2-track road on the left. Proceed about 50 yards on the road and park. Walk about 5 minutes due west (this walk may be strenuous for some). We will remain at this stop for about ½ hour to allow time to walk to the bottom of the kettle.

NOTE: At 2.1 miles drop-off onto surface B (Hughes).

NOTE: At 6.7 miles steep hill marking edge of surface C.

Turtle Lake

Return to H-58 and continue north. Travel 8.75 miles to the Log Slide Road. Turn north. Travel 0.75 miles to the Log Slide parking lot.

Log Slide

Return to H-58. Proceed east.

NOTE: At 3.7 miles, the Grand Sable dunes are on the left (north). At the intersection of Newburg and William Hill roads, turn north on William Hill road and travel 0.7 miles to the Sable Falls parking lot. Walk to the Ghost forest then to Sable Falls.

Ghost Forest and Sable falls

Return to parking lot and travel to Grand Marais (east).

Grand Marais harbor

Follow M77 to M28, turn e, follow to US41, N to Marquette.

Meltwater channels

Observe the outwash channels along M-77 as we proceed south. The "terrace"-like appearance of the topography is due to M77 crossing proglacial meltwater terraces at right angles.

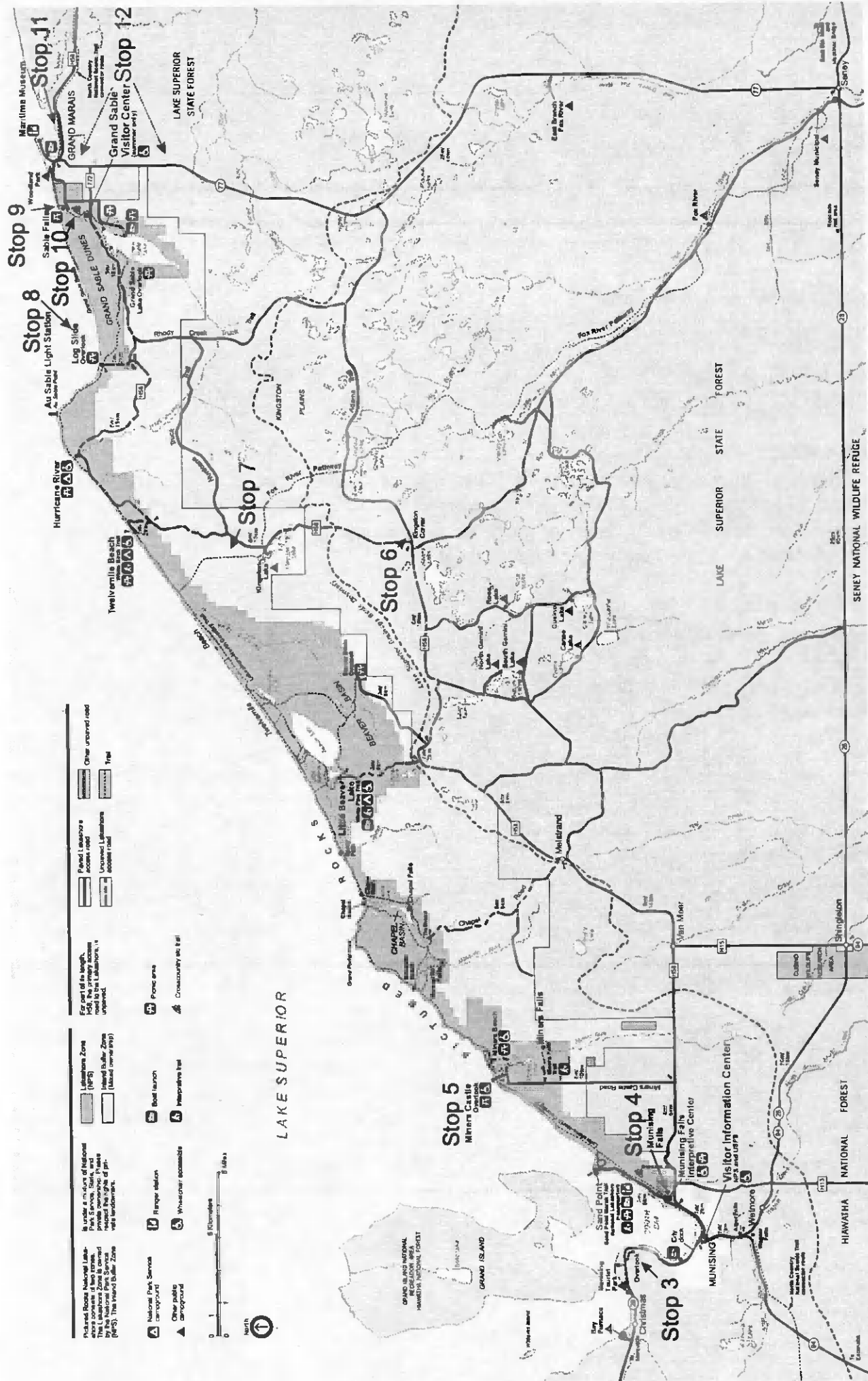
Streamflow was to the east. Note the gentle southward slope of individual terraces, marked by poorly drained, swampy areas near their southern edge.

98 miles to Marquette. Sleep!

Grand Marais to M-28 south on M-77

West on M-28 to U.S. 41

North on U.S. 41 to Marquette



Paleozoic and Pleistocene Geology from Au Train to Grand Marais, Michigan (FIELD TRIP #4)

by Robert S. Regis and John B. Anderton
Northern Michigan University

The geological history of the Pictured Rocks National Lakeshore (PRNL) is limited to two intervals of geologic time; the Pleistocene epoch when glaciers reworked and mantled the underlying bedrock with a nearly continuous veneer of drift, and the late Proterozoic, Cambrian and early Ordovician periods when sediments deposited in shallow seas became the sandstones that form the "pictured rocks" section of the lakeshore.

Late Proterozoic/Cambrian/Ordovician History of the Central Upper Peninsula including PRNL

Most material for this section was compiled from Hamblin (1958), who performed a detailed study of the Cambrian rocks outcropping in the PRNL and elsewhere in northern Michigan. The Paleozoic geologic history of the PRNL is best described as a period of eroding highlands and sedimentary deposition into transgressing empeiric seas. The Northern Michigan Highlands and the Wisconsin Arch stood as eroding remnants of former highlands and mountains, trending east-west across northern Michigan and more north-south across Wisconsin, respectively. Encroaching shallow seas (the Sauk transgression) during the late Proterozoic and throughout the Cambrian were the depositional journey's end for most of the eroded sediments.

Bedrock is best exposed in the pictured rock section where bluffs rise up to 200' above Lake Superior and extend seventeen miles from Munising to the Beaver Basin. For a short distance inland from the escarpment, usually no more than several hundred yards, bedrock may be seen in occasional outcroppings. Elsewhere in the National Lakeshore bedrock is only found in the vicinity of the Grand Sable bank, where it forms a low bluff around the north and east side of Au Sable Point, and in the gorge at Sable Falls.

On this field trip, we will observe the rock formations in reverse order. The first rocks we will see are the youngest exposed in the park (western end) and last rocks we see are the oldest (eastern end). The Jacobsville sandstone, of questionable late-Proterozoic to lower and middle Cambrian age, is the oldest formation in the lakeshore (more than 520,000,000 years old). It is a feldspar-rich, quartz sandstone, deep red in color with white mottlings. Although the Jacobsville has a thickness of 1100 feet, only the top several feet rise above lake level, and only in the eastern part of the park. On this trip, we will see the Jacobsville at Sable Falls (Stop 10).

The early-to-middle Cambrian-age Munising formation underlies most of the lakeshore, and forms most of the significant bedrock outcroppings in the park. It lies unconformably on top of the Jacobsville sandstone. The Munising Formation is divided into two members, the lower Chapel Rock (Stops 10 and 5) and the upper Miners Castle (Stops 4 and 5) members (500 - 520,000,000 years old). Except where the friable Miners Castle member is being rapidly undermined by wave action it forms slopes rather than cliffs.

In the western half of the "pictured rocks" the late Cambrian Au Train formation crops out only along the top edge of the cliff (480 - 500,000,000 years old). The Au Train is a light brown or white, hard, dolomitic sandstone usually highly glauconitic. Where present, it forms a

cap rock on the weaker Miners Castle member. We will observe the "type locality" of the Au Train formation at Au Train Falls (stop 1) on this field trip.

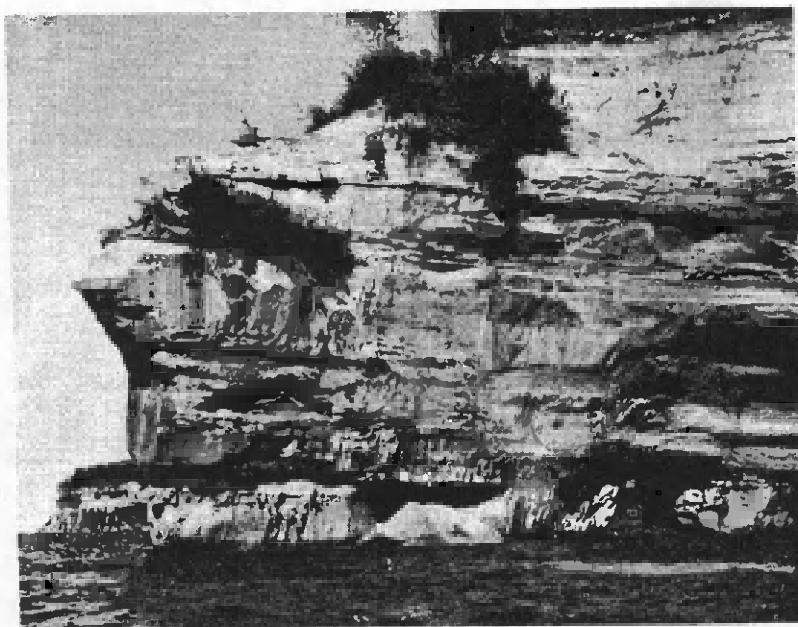
All formations dip toward the south a degree or two as shown in the photo here (view is toward the east). All the formations also arise eastward so that the Au Train formation is missing east of Miners Castle but the Jacobsville, which is below lake level at Miners Castle, carries above lake level. East of Miners beach, it is well exposed beneath the conglomerate of Chapel Rock and in the gorge at Sable Falls.

There are many waterfalls along the escarpment formed mostly by the Au Train formation, but all are fed by small streams with small watersheds and are only imposing in the spring and during wet periods.

Munising Falls (stop 4) is the most unusual and interesting of the falls. It is

an extremely well-developed cap-rock waterfall with the Au train Formation forming a shelf that overhangs the Miners Castle member by 25 to 30 feet permitting observers to walk behind the torrent which falls from the center of the overhang as a concentrated stream and then descends another 30 to 40 feet in a series of cascades. A recent collapse of a section of this formation onto the walkway prompted Park officials to close a part of the walkway. Some well developed potholes may be seen in the cataract section. Miners Falls has developed where the Miners River drops from the upper to the broad lower valley. The fall is vertical and about 30 feet high. Chapel Falls is fed by a tributary to Chapel Lake that courses down the valley slope where there is no cap rock. The fall is a long cascade, about 90 feet high that broadens fan-like from ten feet at the top to 30 feet at the bottom. Bridalveil Falls and Spray Falls are formed where streams fall, about 90 feet, directly into Lake Superior, adding greatly to the beauty of the Pictured Rocks. At Sable Falls, the stream draining Grand Sable Lake cut into the Chapel Rock and Jacobsville formations where they lie beneath sand dunes. The deeply wooded setting is exceptionally beautiful and is but a short walk from the lakeshore and the parking lot.

The Pictured Rock escarpment has been carved, by frost action and wave erosion of the present lake, as well as higher stages, into a variety of shore cliff features such as: stacks, caves, sea arches, and promontories. These features have been named: Lovers Leap, Rainbow Cave, Grand Portal, Miners Castle, Chapel Rock, The Battleships, Flower Vase and Indian Drum Cave. Most of the features can be reached by hiking but only Miners Castle is accessible by automobile. The best way to appreciate the cliffs is by boat tour. Increased accessibility by land will not diminish the advantage of viewing the cliffs from the water.



View along the Pictured Rocks showing the Munising formation dipping to the south at a low angle.

Late Quaternary History of the Central Upper Peninsula including PRNL

The Great Lakes region experienced repeated glaciations and concomittant inundation by proglacial lakes throughout the Quaternary. For the purposes of this fieldtrip, the final major deglaciation of the area during post-Twocreekan times (i.e. 11,800 BP) marks the beginning of the portion of Late Quaternary history that is most relevant. Between 11,800 and 11,500 the Superior Ice Lobe nearly completely covered the Upper Peninsula (Farrand and Drexler 1985). By about 11,500 BP, retreating glacial ice, followed closely by the high stands of Glacial Lake Algonquin, had nearly left the region (Larsen, 1987; Futyma, 1981). The retreat of ice continued, opening up large portions of the Lake Superior basin in what is known as Glacial Lake Duluth (Phases A and B), allowing discharge from Glacial Agassiz during Post Algonquin times (ca. 10,700 BP); however, evidence of this period was largely obliterated by a final readvance of ice into the Lake Superior basin. The glacial readvance is known as the Marquette advance (Drexler et al. 1983).

Shoreline features created by these earlier lake stages in the Lake Superior basin were largely destroyed during the Marquette Advance (Hughes, 1978; Drexler, 1981; Farrand and Drexler, 1985). By about 9800 BP, the ice had begun to retreat again, resulting in a stepwise drop in lake levels which initiated the Post Duluth Phase lakes (Farrand and Drexler 1985). After about 9,800 BP, Marquette Advance ice had retreated far enough to the north to allow lake water from the western part of Superior basin to drain eastward and southward, eventually creating the Main Minong Phase (Farrand and Drexler, 1985). However, catastrophic discharge from Lake Agassiz early in the Nipigon Phase is thought to have breached a till barrier at the east end of the Lake Superior basin, causing a decline in Lake Minong resulting in at least five or six post-Minong levels in the Superior basin (Farrand, 1960; Teller and Thorleifson, 1983). The lowering was finally stopped as resistant bedrock at the Sault outlet was reached, culminating at the Houghton Low around 8000 BP, the lowest lake phase in the Superior basin. Finally, as the ice left the south shore of the basin, Glacial Lake Minong formed along the margins of the retreating glacier reaching its maximum expression by about 9500 BP; however, shortly afterwards the retreating ice front in the eastern Great Lakes revealed the isostatically depressed North Bay outlet, resulting in falling lake levels known as the Houghton Low. During this period, lake levels in the Superior basin dropped to their all time lowest elevation, which may have allowed many rivers to deeply incise their valley channels. By about 8000 BP the bedrock sill at the Sault acted to halt falling lake levels in the Lake Superior basin; however, by then isostatic uplift had acted to raise the elevation of the North Bay outlet, resulting in rising lake levels in the southern basins.

Eventually, the rising lake levels reached the elevation of the Sault Outlet and lake levels in the Superior basin began to gain in elevation. During this period, known as the "Nipissing Great Lakes," water in the basins of Lake Superior and Lakes Huron and Michigan joined together to create one huge lake, which was controlled by the North Bay outlet. Notwithstanding, the North Bay outlet continued to rise and eventually lower drainages to the south became active commencing the three-outlet (Chicago, Port Huron, and North Bay) phase of Lake Nipissing (Nipissing I), which reached its maximum elevation between 4700 and 4000 BP (Hansel et al. 1985). During the Nipissing Maximum, flooding of many tributary river valleys created large embayments along the coastal areas of the Upper Peninsula (Anderton 1993a).

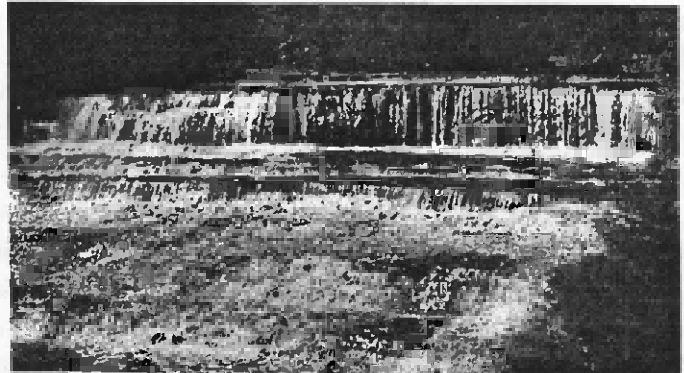
The Nipissing II phase, marking a slight drop in levels, was attained about 4000 years BP as continued isostatic uplift raised the North Bay outlet above the altitude of the two southern outlets (Hansel et al. 1985, Larsen 1985b). Following the Nipissing II phase, lake-levels began to

fall as downcutting progressively lowered the Port Huron outlet and water volumes fluctuated in the basins. A short peak in lake-levels at about 3200 BP resulted in the Algoma phase, but by about 2200 BP lake-levels in the Lake Michigan-Huron basin had fallen below the elevation of the rebounding sill at the Sault, separating the Superior basin from the lower Great Lakes and initiating the Sault level (Farrand 1960). Modern lake-levels in both the Lake Superior and Lake Michigan-Huron basins were finally attained by about 2000 years ago.

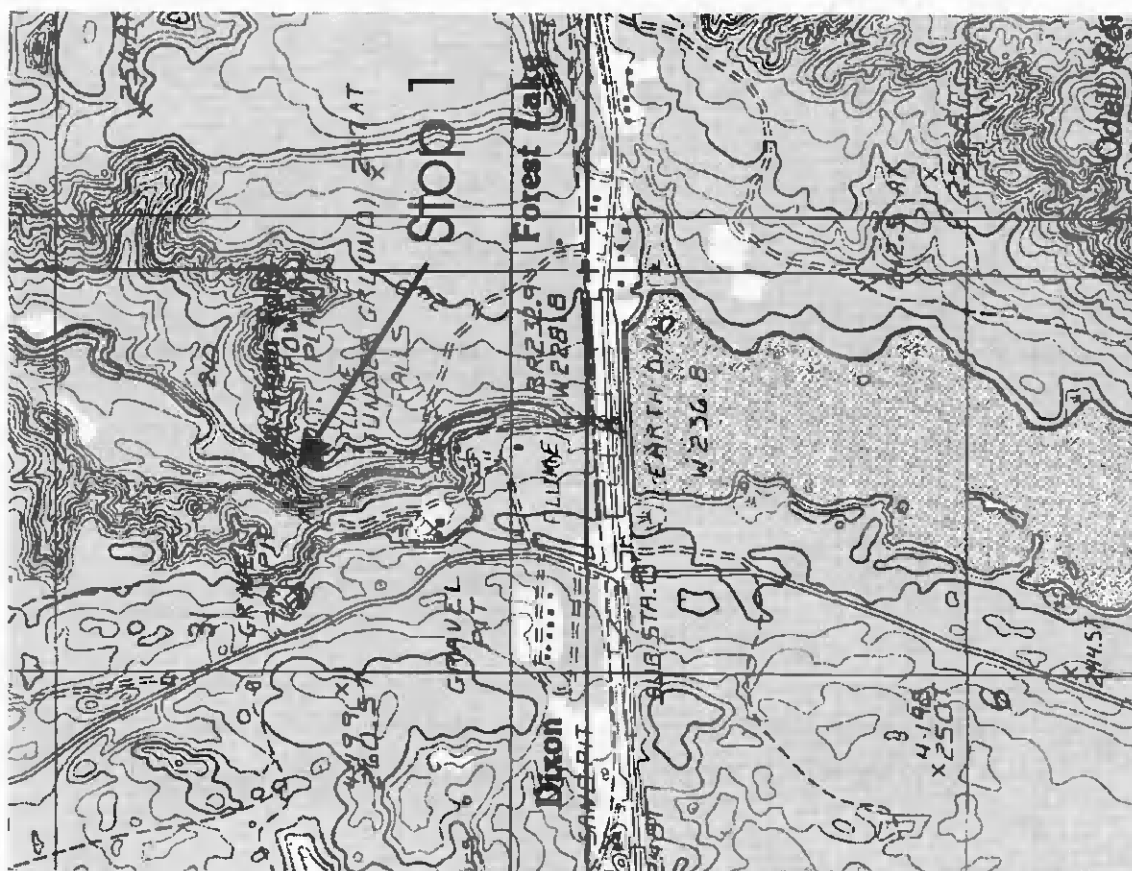
Larsen (1985), working in the southern portions of the Lake Michigan-Huron basins, has also proposed an alternative model of Holocene lake-level fluctuations, which suggests a complex record of climate-related changes that lasted between 200 and 300 years each and fluctuated with an amplitude of 1 to 2 meters above the apparent mean lake level. In the last 7000 years at least eight episodes of high water periods separated by intervening low water periods are recognized (Larsen 1985).

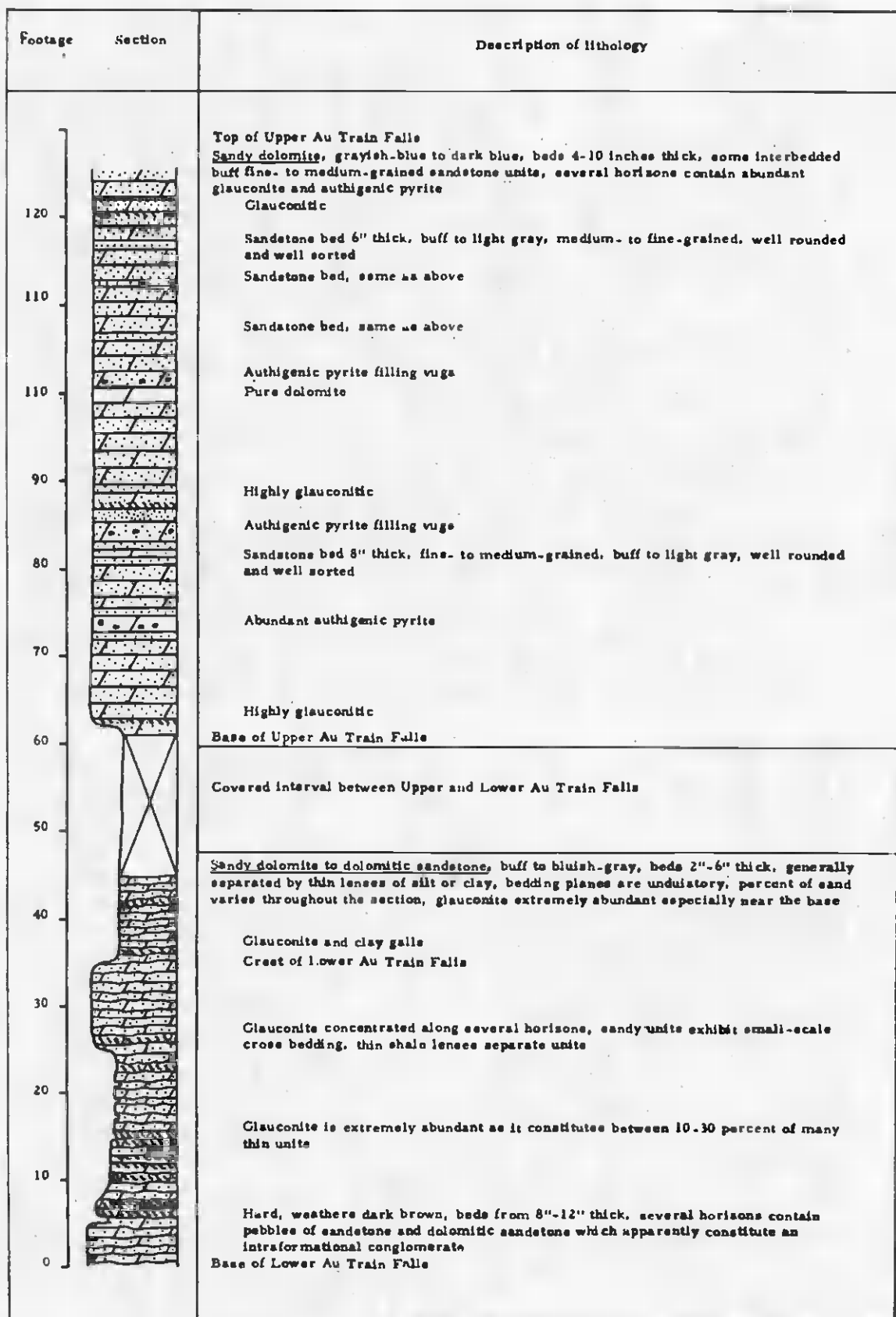
Stop 1. Au Train Formation at Au Train Falls

At Au Train Falls, a 30 meter thick section of the 100 meter thick early Ordovician Au Train Formation (aka Trempealeau Formation) is exposed. The formation consists of 2 parts, the upper and lower members. At this stop, we will examine the lower section at the lower falls, and walk to an overview of the upper section, which is exposed about 200 meters upstream, but is relatively inaccessible. The Au Train Formation lies unconformably upon the Munising Formation, and is representative of the continued Sauk sea marine transgression that began in the late Proterozoic. The environment of deposition was a shallow shelf platform with fluctuating sea levels. Paleogeographically, the region was equatorial with the equator trending nearly north-south compared to modern orientation.



Note the step-like character of the falls (also in the upper falls) created by the alternating layers of dolomite, shale, and sandstone of varying degrees of resistance. Near the base of the lower falls are a series of thin beds of glauconitic sandstone (hydrous silicate of iron and potassium) and shale. Glauconite is disseminated as flakes throughout the sandstone. Glauconite comprises as much as 35% of some beds in the lower section and imparts a speckled green to dark green color to the formation. Individual beds vary from pure sandstone to pure dolomite (Hamblin, 1958). Dolomitic beds are bluish gray in color. An intraformational conglomerate(?) with pebbles of sandstone and dolomitic sandstone are found in a few of the units near the base of the section (see cross section on next page). At the base of the lower Au Train, the contact with the underlying Miners Castle member of the Munising Formation is easy to recognize because the friable sandstone is quite different in appearance from the hard, resistant dolomitic sandstone of the Au Train. Fossils are rare in the Au Train but become abundant in later formations. Following deposition of the Au Train Formation was a minor regression that formed an unconformity.





Columnar section of the Au Train Formation at Au Train falls (Hamblin, 1958)

Stop 2. Au Train-Whitefish Channel, Barrier, and Beach Ridge Complex

Au Train Whitefish Channel

The Whitefish-Au Train Channel is a former proglacial lake spillway that drained across the central Upper Peninsula. From Little Bay De Noc, north to Au Train Bay on Lake Superior, the channel is over 60 kilometers (36 miles) in length and ranges between about 2.5 kilometers (1.5 miles) to 6.7 kilometers (4 miles) in width. The Whitefish River, a tributary to Little Bay De Noc, drains the southern two-thirds of the Channel. The northern third is drained by the Au Train River, a tributary to Lake Superior. Most of the channel bottom is underlain by thin deposits of gravel or till over bedrock.

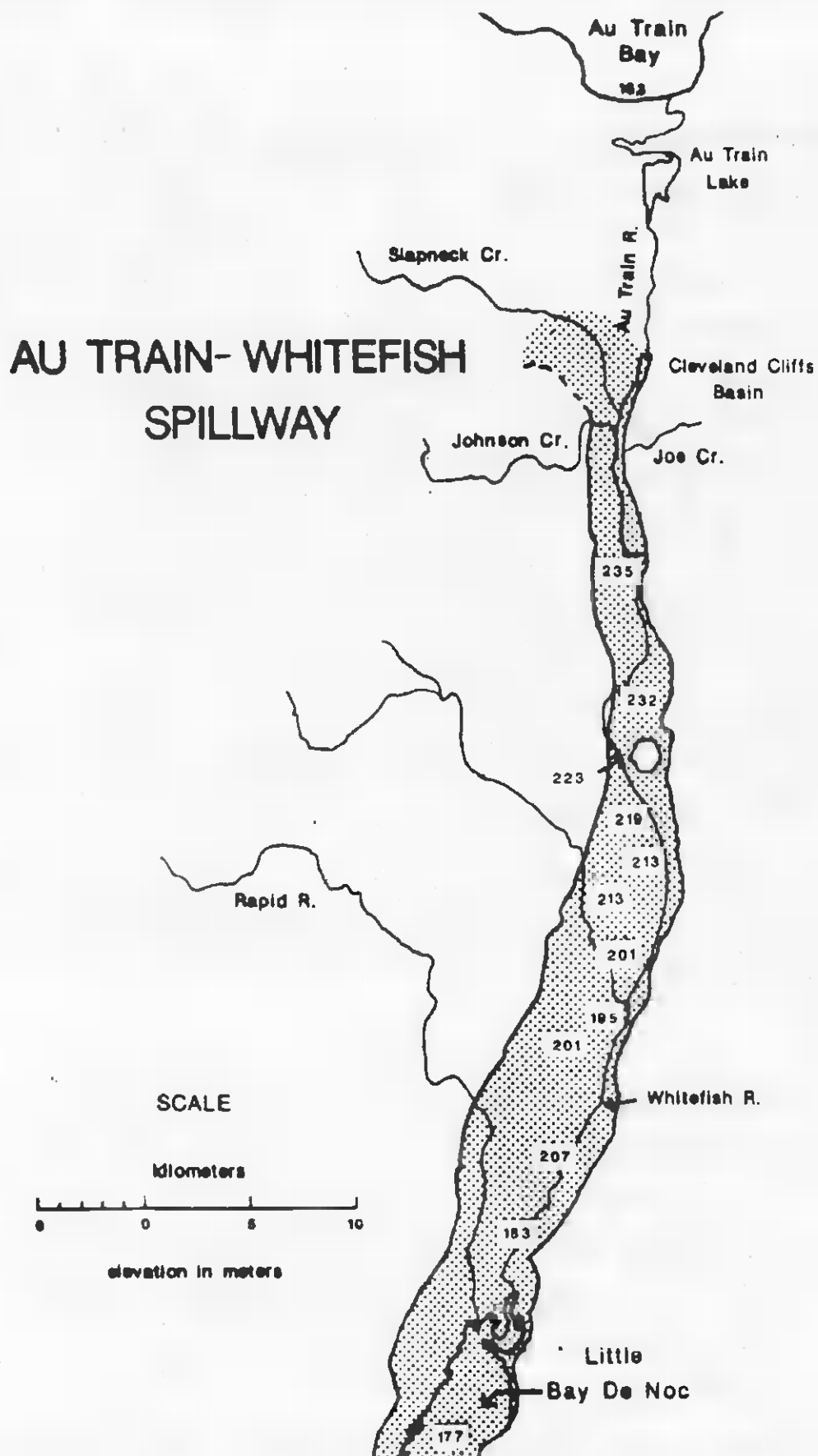
The lowlands of the Au Train-Whitefish Channel were first noted by Foster and Whitney (1851), but it was Winchell (1871) who interpreted the feature as a meltwater spillway. Russell (1904), however, identified the channel sides as kame terraces having been deposited by a thin lobe of ice that had stretched across the Upper Peninsula. The channel has since been studied by a number of workers including Leverett (1929), Hough (1958), Drexler et al. (1983), Farrand and Drexler (1985), and Hughes (1990). Incidentally, Leverett (1929) indicates that during the 1920s, government engineers considered cutting a ship canal through the Au Train-Whitefish Channel and connecting Lake Superior to Lake Michigan, thus avoiding the Sault Locks.

According to Hughes (1990), the Au Train-Whitefish Channel reached its full expression during the Marquette Advance about 10,000 BP. At this time, lake levels in the Lake Michigan-Huron basins were extremely low (Chippewa-Stanley Low) as retreating ice had revealed the isostatically depressed North Bay outlet, allowing water to nearly drain from the southern basins. Before, during, and, for an unknown period after the Marquette Advance, proglacial lake water drained across the central Upper Peninsula to the lower lakes, creating the Au Train-Whitefish Channel. Hughes (1990) has suggested the Channel extends under Little Bay De Noc and Green Bay to a large, Chippewa-level delta submerged off the east side of the Door Peninsula. The Channel was abandoned at around 9700 BP when retreating ice allowed lake water to reach the Sault Outlet on the east end of the Superior basin.

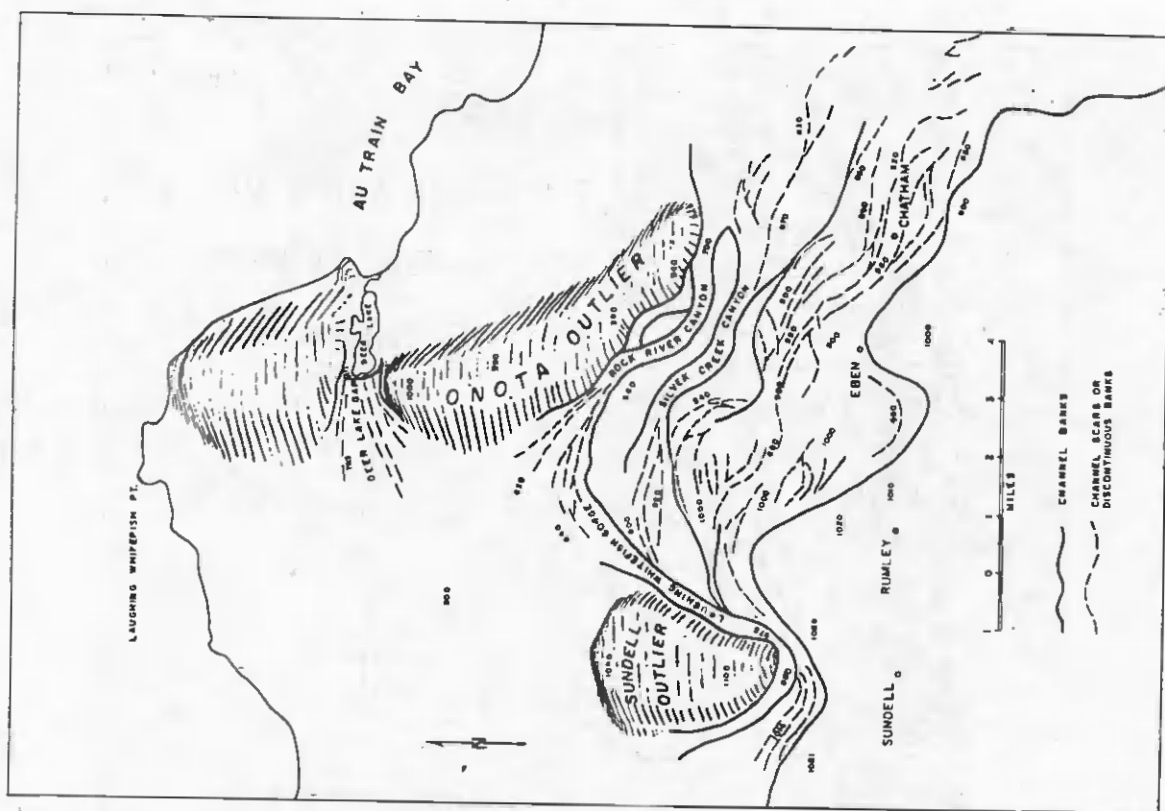
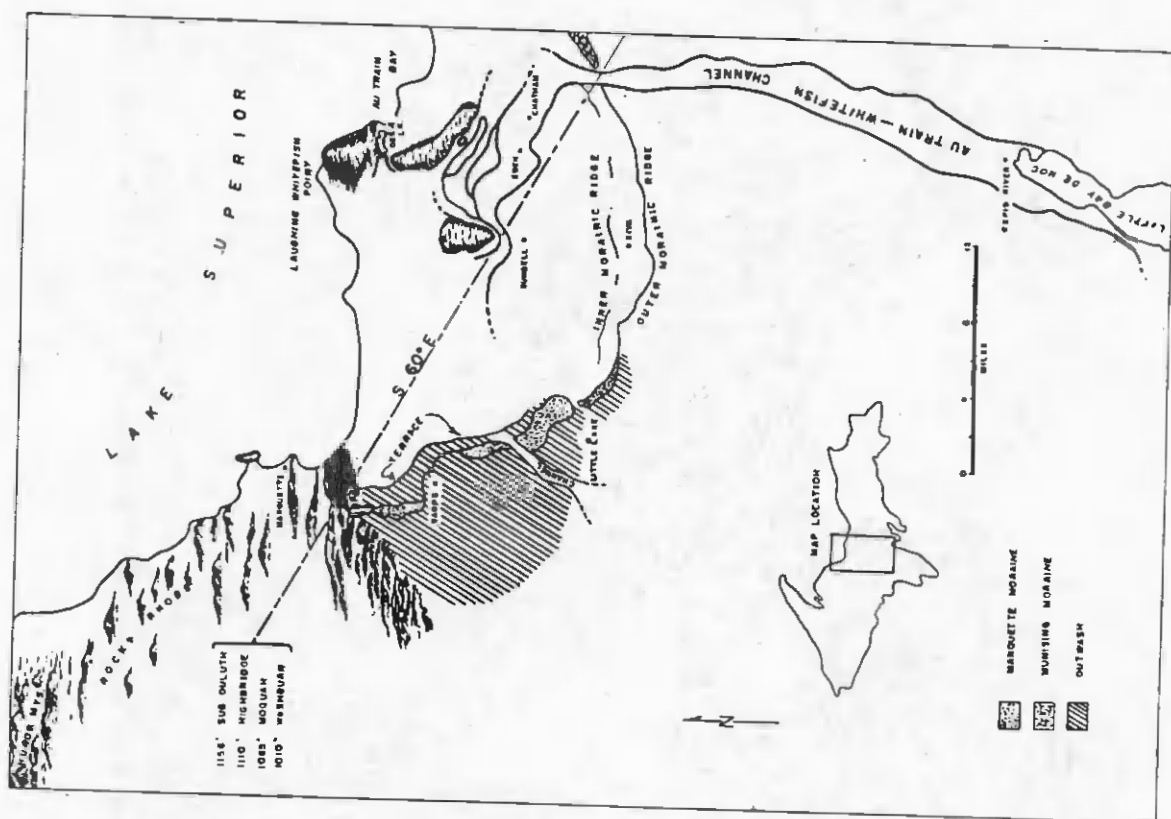
Au Train Barrier

During Nipissing times, lake water flooded some 6 kilometers (3.6 miles) into the northern end of the Au Train-Whitefish Channel creating Au Train Relict Bay, which is one of the largest Nipissing embayments in the central Upper Peninsula. Nipissing I wave-cut bluffs and cliffs, cut in bedrock and unconsolidated sediments at 192 meters, rim much of the east and west sides of the former embayment; however, in places along the southeast fringes, the shoreline is less developed, appearing to have been modified by eolian activity. In fact, small relict foredunes may be present along the southeast side of Au Train Lake. A massive mid-bay barrier extends from northwest of Paulson Lake, east to Joel Creek, forming the northern boundary of modern Au Train Lake. The barrier, having an elevation of 186 meters on its north side and 189 meters on its south side, reaches an elevation at its crest between 195 and 192 meters and a maximum elevation of 201 meters on what appears to be a dune remnant. In places, the barrier has been severely eroded by the Au Train River.

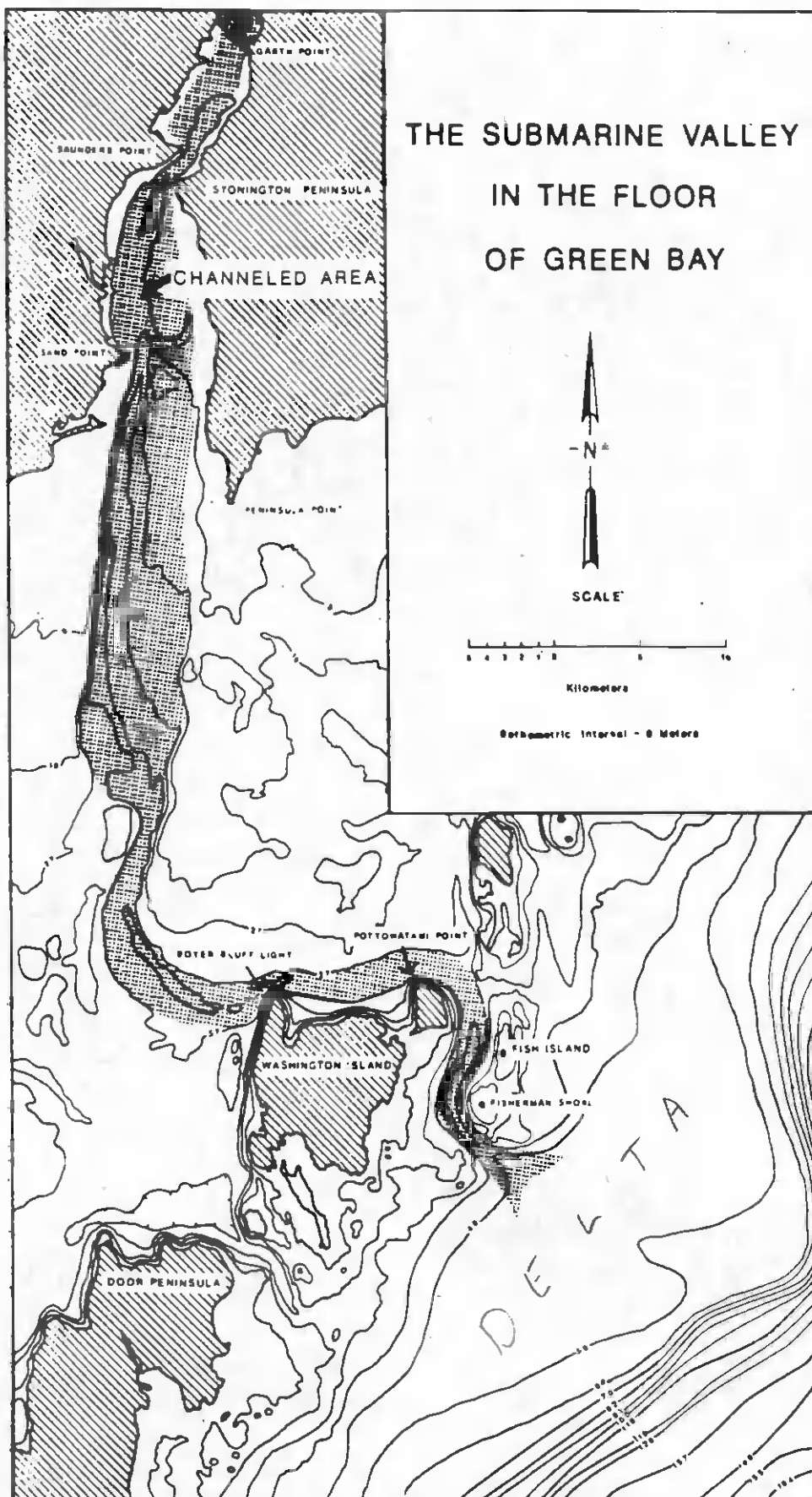
The barrier created a huge lagoon between the barrier proper and the southern rim of the bay, now occupied by Au Train Lake, Paulson Lake, and surrounding wetlands. Based on the depth of Au Train Lake (USDA, 1938), during Nipissing I times, the lagoon would have had a maximum depth of at least 7.5 meters (25 feet), an average depth of 3 to 4 meters (9.8 to 13 feet), and covered about 6 square kilometers (2 square miles). Drainage may have exited from the



AuTrain-Whitefish Spillway (Hughes, 1971)



Moraines and channels in the Marquette area and the Eben-Chatham channels (Hughes, 1971)



lagoon on its northeast corner near the eastern end of the Au Train Barrier or at some mid-position breach in the barrier, where the Au Train River runs through today. Nipissing II levels may have modified the northern edge of the barrier, which is at an elevation of 186 meters.

Au Train Beach Ridge Complex

The Au Train Beach Ridge Complex occupies the area between the barrier and the modern shoreline of Lake Superior. The complex is composed of some 50 separate recessional ridges which form a compact, arcuate shaped "corrugated plain" as first termed by Bergquist (1936). The ridges, which range in elevation between 186 and 184 meters, are currently being eroded by Lake Superior, which has created an irregular line of actively forming coastal foredunes on the northern end of the complex. The Au Train River has also meandered through the ridges resulting in erosion and truncation, suggesting that the river's present course is relatively recent. The ridges are parallel to each other, and there is no evidence of cross-cutting relationships, indicating fluctuating lake levels.

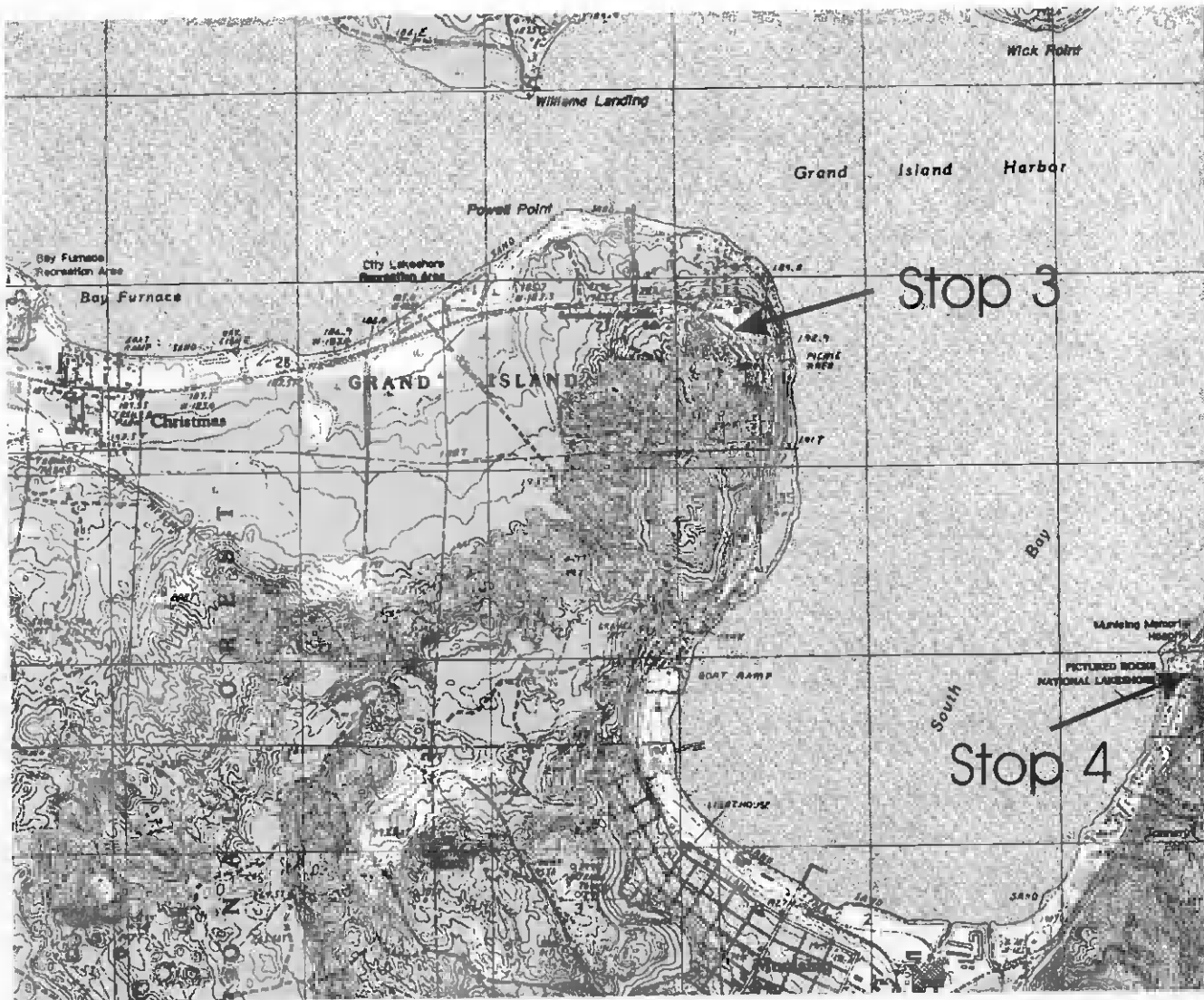
Stop 3. Grand Island/Powell Point Scenic Overlook

This stop is on the crest of a Marquette Advance moraine. The overlook affords a view of Grand Island, Grand Island Harbor, Murray Bay, and Sand Point. Sand Point, a large cusped spit, is visible in the east channel of Grand Island Harbor. The spit, which ranges in elevation between 185 and 183 meters, appears to have formed in post-Nipissing times, and is still being actively modified by wave-action from Lake Superior. It is composed of a number of lesser sandy barriers that appear to have created smaller lagoons during the development of the spit. A massive Nipissing I, wave-cut bluff at 192 meters is present along the southeast side of the spit, marking the start of the modern cliffs of the Pictured Rocks, which extend to the northeast from Sand Point.

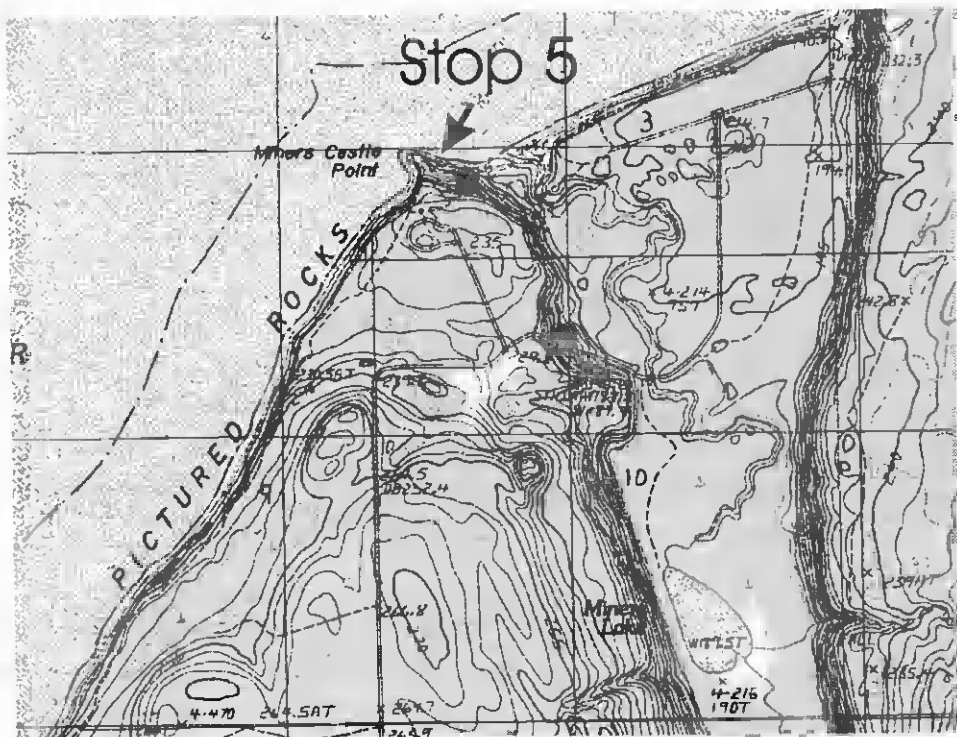
On Grand Island, Nipissing I wave-cut bluffs developed in bedrock at 192 meters rim much of the southern portions of island. Wave-cut caves, shoreline stacks and arches, and pocket beaches are present along the Nipissing I shoreline along the west side of Murray Bay. Wave-cut bluffs at 192 meters rim portions of the Island's western high ground, known locally as the Thumb. A well-developed system of stream gullies has dissected the eastern hillsides of the main lobe of the island, as well as much of the hillsides on the Thumb. These narrow, deep incised valleys end abruptly at the Nipissing I shoreline, indicating that they formed in pre-Nipissing, Houghton Low times when stream base levels were extremely low.

Cusped barriers grading from the Nipissing I bluffs to about 186 meters are also visible on Grand Island. The most obvious of these is the Duck Lake Cusped Barrier, which is located on the east side of the main lobe of the island. It is composed of a number of large ridges that trend east to west on the south side, and north to south on the east side of the barrier. Duck Lake, a small inland lake, is a lagoon remnant associated with the barrier. The Muskrat Point Cusped Barrier, formed off the southwestern end of the Thumb, also contains a lagoon remnant, now a small swampy pond. Wave action from Lake Superior has eroded the southeastern tip of the Duck Lake Cusped Barrier, the southern limb of the Muskrat Point Cusped Barrier, and the southeastern tip of the Williams Landing Spit, exposing imbricated gravel and cobble beds in both cases. These eroded areas show up as high, sandy bluffs along the modern shoreline.

The Grand Island Beach Ridge Complex, a complex of at least 25 beach ridges ranging in elevation between 186 and 183.5 meters, forms a tombolo between the Thumb and the main part of the island. In places on the southern edge of the complex, beach ridges are submerged by



Stops 3 & 4



Stop 5

Lake Superior, while the northern edge is currently being eroded by the modern lake, creating small coastal foredunes along Trout Bay.

A steep cliff visible high on the west side of Grand Island presents an enigma. Some workers (Dorr and Eschman, 1971) have suggested it is a wave-cut bluff from Lake Algonquin. However, such a feature would have been destroyed during the Marquette Advance. Alternatively, the escarpment may be a remnant of an ice marginal stream channel created during the retreat of Marquette Advance ice or it may have been created by headward erosion and retreat of a caprock on the highest portions of Grand Island.

Stop 4. Munising Falls

At Munising falls, the Au Train Formation (see stop 1 for a more complete description) forms a resistant caprock of dolomitic sandstone about 5 meters thick. Conformably below is the weaker Miners Castle member of the Munising Formation, which has been undercut to form a steep high-walled valley. Munising Creek plunges 10 meters over the falls in its short journey to Lake Superior. At the base of the falls are several potholes and plunge pools. They were abraded into the sandstone by hard cutting tools carried from the overlying caprock and from glacial drift. Visitors used to walk behind the falls, underneath the overhanging caprock, but a recent collapse of a section onto the walkway prompted park officials to close that part from the general public.

The Munising formation represents a transgression of the shallow Sauk sea onto the mid-continent region in Cambrian time. The upper Miners Castle Member is a light gray to white colored, poorly sorted, cross-bedded sandstone that comprises the upper 30 meters of the Munising Formation. In the lower part of the member, thin lenses of blue shale are common, but become scarce in the upper portions. Quartz grains dominate the lithology (>95%) of the Miners Castle member, with feldspar comprising most of the remainder. Most quartz grains exhibit straight extinction and are likely of igneous origin. It is not uncommon to find 1-3 cm thick beds of shale alternating with 10 cm thick beds of coarse sandstone and even conglomerate! Especially in the lower parts of the Miners Castle member. Higher up in the member, fewer beds of shale and conglomerate are found, and beds consist mostly of well-sorted, cross-bedded sandstones with a greater degree of mineralogical and textural maturity. Some individual beds are quartz arenites, but in sum the formation is poorly sorted. Quartz is also the dominant cementing agent, but with only slight secondary enlargement of the detrital grains, it is porous and friable. Authigenic pyrite is common enough in some of the middle beds that it is megascopically discernable. Discussion of the Miners Castle member continues at the next stop.

Stop 5. Miners Castle

This stop examines the type locality of the Miners Castle member of the Munising formation (see description in stop 4). Sedimentary structures such as mud cracks (mostly in the shale beds), ripple marks and cross bedding (as seen at this stop) suggest an alternating fluvial/lacustrine environment of deposition. Significantly, the ripple marks and cross bedding in the Miners Castle member indicate a transport direction from the east-northeast, as opposed to the northwesterly transport direction measured in the older Chapel Rock member (see figure illustrating cross-bedding directions). The abrupt change in transport directions in the two members provides further evidence of an unconformity that separates them. The change in transport direction also suggests that the Wisconsin Arch and the Northern Michigan highlands,

Miners Castle Member of the Munising Formation

Au Train Formation

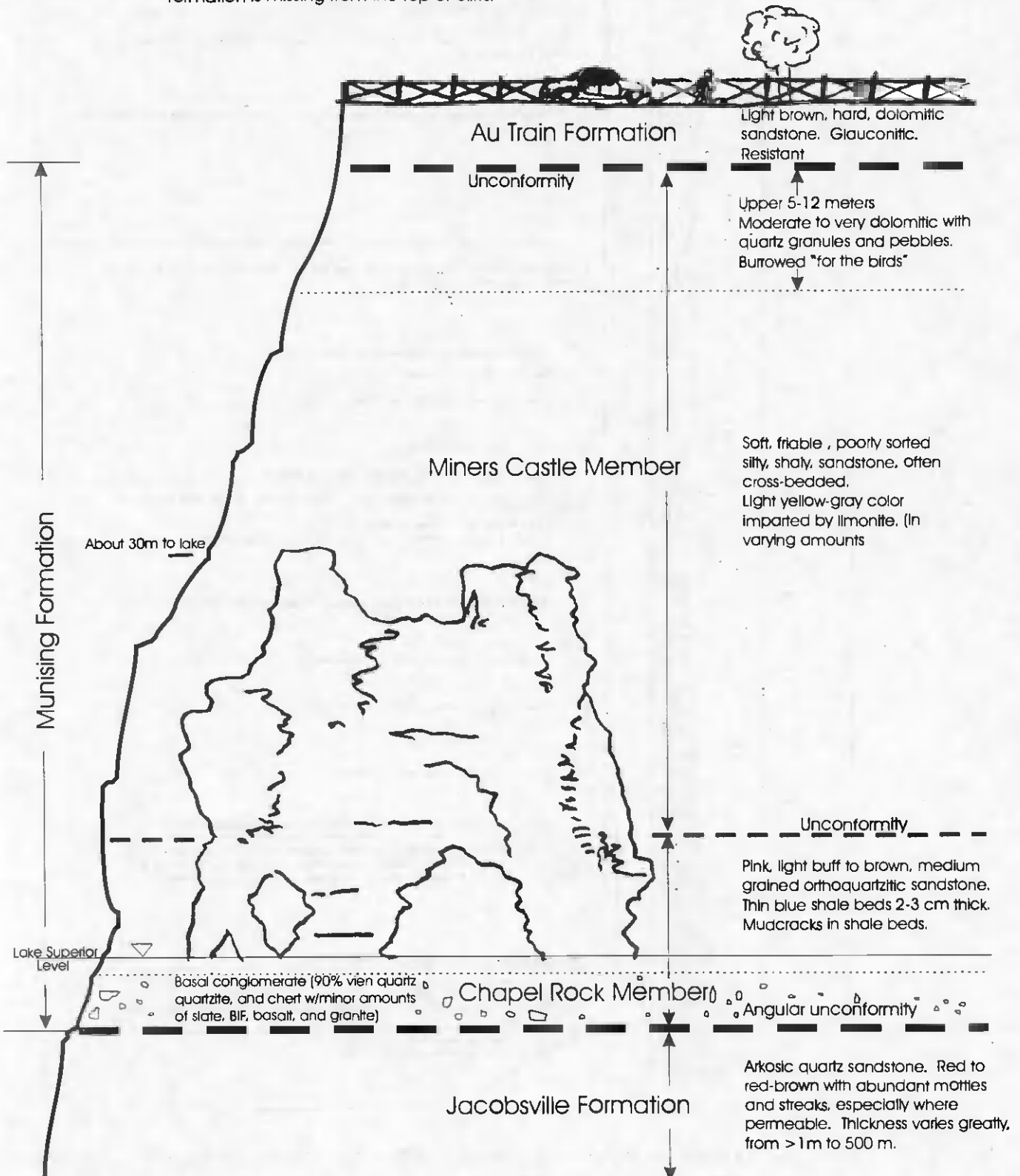
- 148' - 152' Sandstone, very dolomitic, yellow-brown, coarse-and medium grained with much very coarse and little fine, scattered very fine and fine quartz pebbles. Some zones conglomeritic. Massive bedded and irregularly bedded. Some large sandstone pebbles.

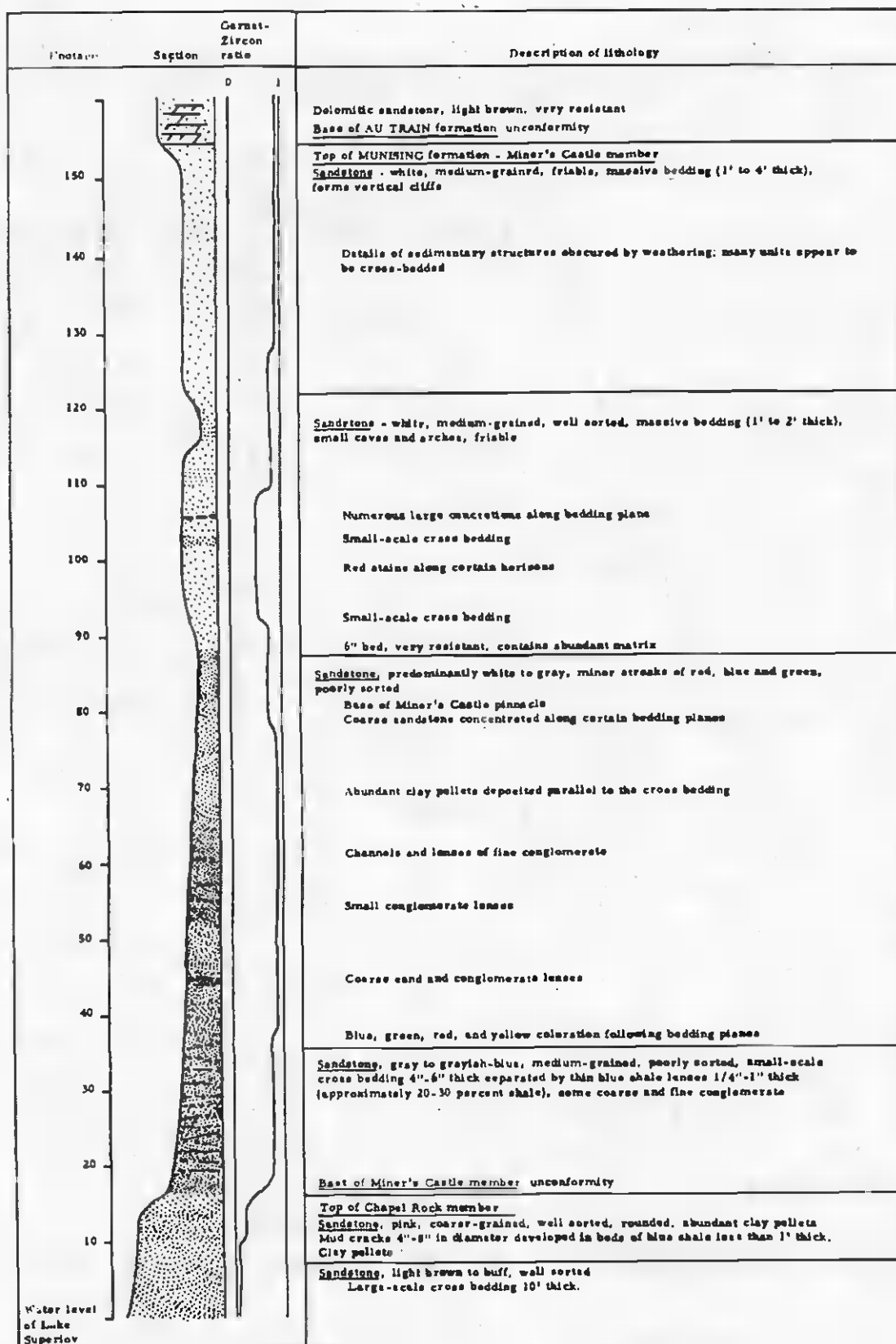
Munising Formation, Miners Castle Member

- 144' - 148' Sandstone, light yellow gray, medium grained with much fine and a little fine, even bedded and thin-medium beds.
- 140' - 144' Another bed as above
- 122' - 140' Inaccessible
- 121' - 120' Light yellow-gray sandstone, coarse and very coarse grained with a trace of granules. Cross-bedded in medium-thin beds.
- 115' - 121' Light yellow-gray sandstone medium to fine grained with traces of granules. Medium - thick bedded with cross bedding. Poorly sorted with much fine material in lower foot of bed.
- 112' - 115' Light yellow gray sandstone, coarse to medium grains. Trace of granules. Massive, cross bedded.
- 111' - 112' Light yellow gray sandstone, poorly sorted with sizes ranging from silt to granules. Abundant limonite staining. Appears to be burrowed. Narrow ledge.
- 108' - 111' Light brown gray sandstone. Medium to coarse grained with much fines. Massive. Trace of granules.
- 106' - 108' Light yellow gray sandstone. Poorly sorted with grains ranging from silt to granules. Abundant burrows best seen from overhangs.
- 103' - 106' Light yellow brown sandstone. Medium to coarse grained with few granules. Massive bedded.
- 99' - 103' Same as above except more silty and abundant burrows.
- 95' - 99' Light yellow gray to gray sandstone. Silty medium to fine grained with thin beds of red, blue and green shale. Poorly sorted.
- 40' - 95' Light yellow gray sandstone. Poorly sorted to well sorted beds. The upper part, beginning at the top of Miners Castle pinnacle, consists of medium to fine grained well sorted beds of sandstone, interbedded with poorly sorted beds of sandstone containing abundant silt and thin beds of silty shale, and conglomeritic beds with silty shale pebbles. The upper 6 feet contains burrowed beds. At 10-12 feet below the top, are prominent poorly sorted, shaly, conglomeritic and cross bedded sandstones.
- 20' - 40' Gray sandstone. Poorly sorted, medium grained with abundant thin blue shale partings. Some conglomerate. Cross bedded.
- 10' - 20' Light yellow gray sandstone, coarse grained, well sorted. Contains clay pebbles.
- ### **Munising Formation, Chapel Rock Member**
- 0' - 10' Light yellow gray sandstone. Medium to fine grained with a trace of coarse, well-sorted sandstone. Cross bedded.

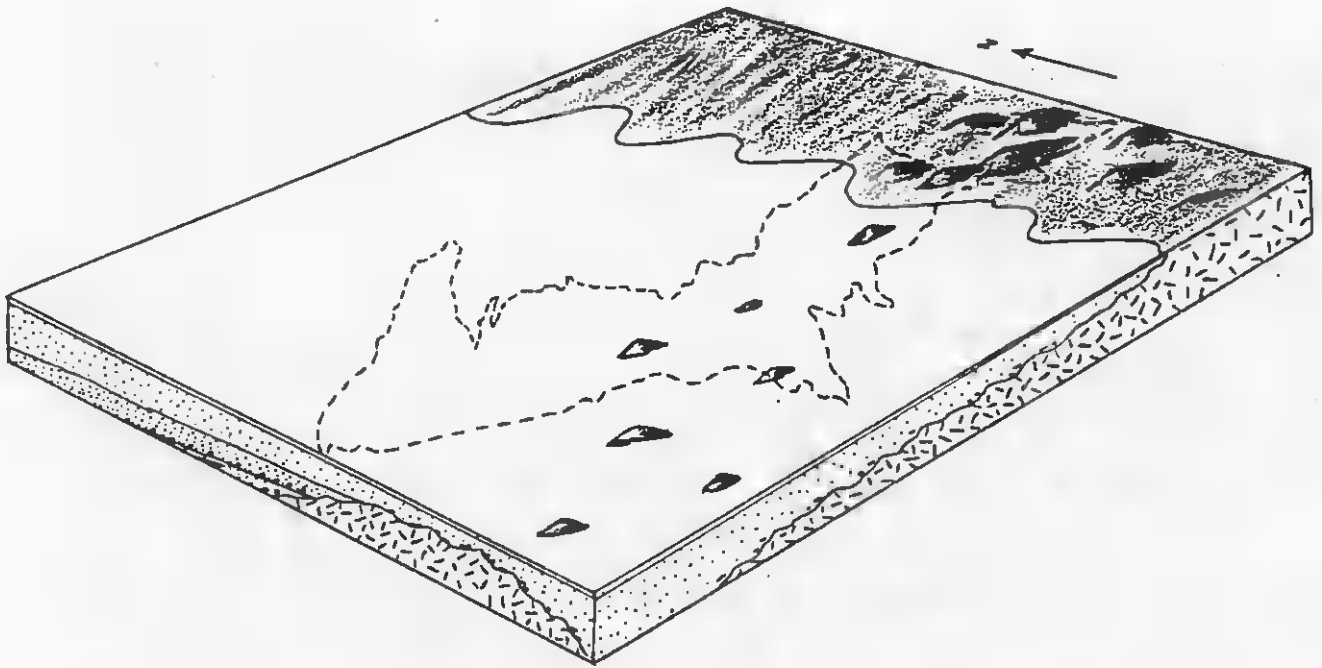
Lake Level = 183 m (602')

All members arise to the east so that Jacobsville is above lake level at Grand Marais and the Au Train formation is missing from the top of cliffs.

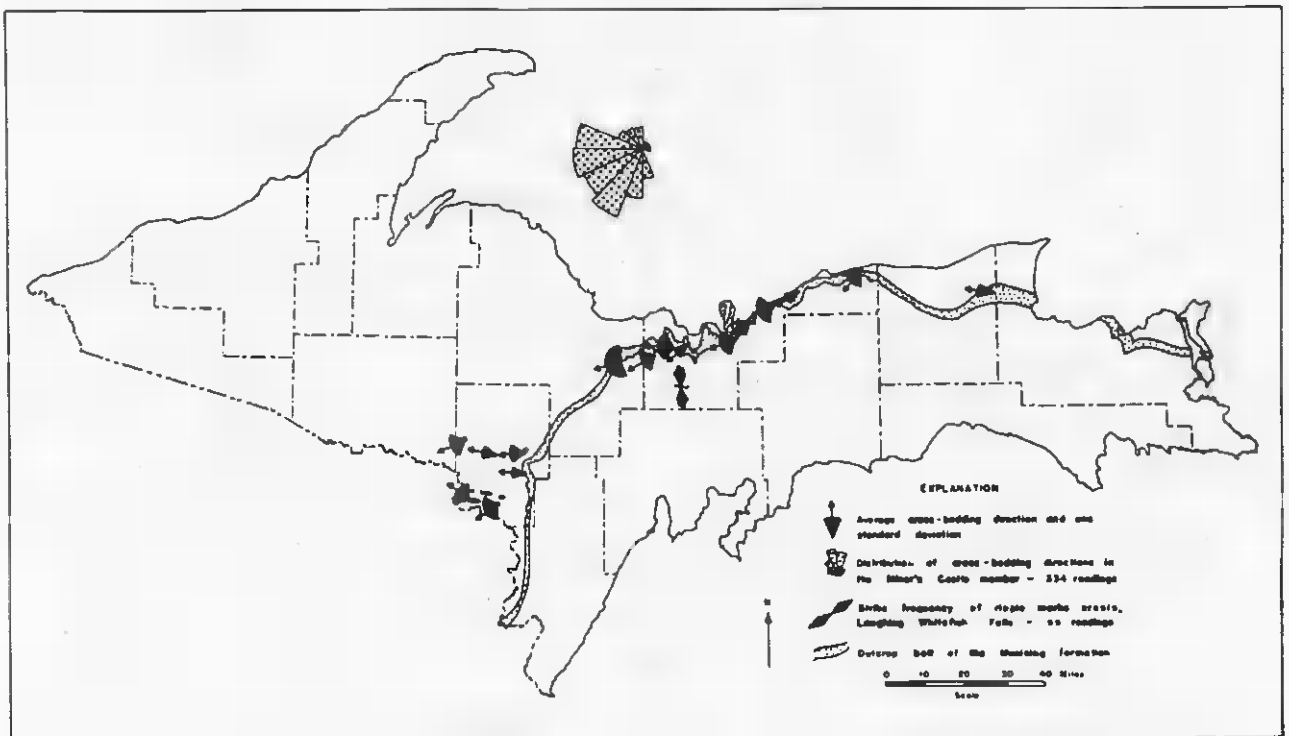




Columnar section of the Miners Castle member of the Munising Formation at Miners Castle (after Hamblin, 1958)



Paleogeography during deposition of the Miners Castle member of the Munising Formation (after Hamblin, 1958)



Cross bedding directions in the Miners Castle member of the Munising Formation (after Hamblin, 1958)

which provided the source for sediments during the Jacobsville and Chapel Rock deposition, had eroded enough that the transgressing Sauk Sea submerged most of the Upper Peninsula and Wisconsin.

Stop 6. Kingston Plain

Stop 6 is on the Kingston Plain, an extensive outwash plain that is located between the towns of Munising and Grand Marais. The Plain presents a unique, prairie-like setting compared to much of the more heavily forested areas of the Upper Peninsula. The multitude of pine stumps preserved on the Kingston Plain serve as testimony to the intensity of historic clear-cut logging.

A number of workers have studied the geology of the Kingston Plain (Leverett, 1911, 1929; Bergquist, 1936; Martin, 1957; Hughes, 1968; Drexler, 1981, Drexler et al., 1981; Blewett and Rieck, 1987; Blewett, 1994), which has resulted in a wide range of theories concerning its formation history. Largely, the controversy has focused on the interpretation of the Munising Moraine, which the Kingston Plain is part of (Blewett, 1994). According to Hughes (1968 and unpublished work), and later by Blewett (1994), whom has done the most current Quaternary geology research in the area, the Plain initially formed when Marquette Advance ice probably reached an equilibrium and southward flowing meltwater streams built the Upper Kingston Outwash Plain surface at about 10,000 BP (Phase I). Ice retreated somewhat from this position, opening up drainage to the east between the ice front and higher ground to the south, creating a channel at 283 m that currently parallels state highway M-77. The upper portions of the Kingston Lake Kettle Chain formed at this time.

Next (Phase II), the ice margin retreated to a new position along the Lower Kingston Plain, opening even lower drainage outlets from the west. Consequently, water flowing to the east between the ice front and the now abandoned Upper Kingston ice-contact slope, formed a broad, kame terrace at about 285 m, which slopes to the east.

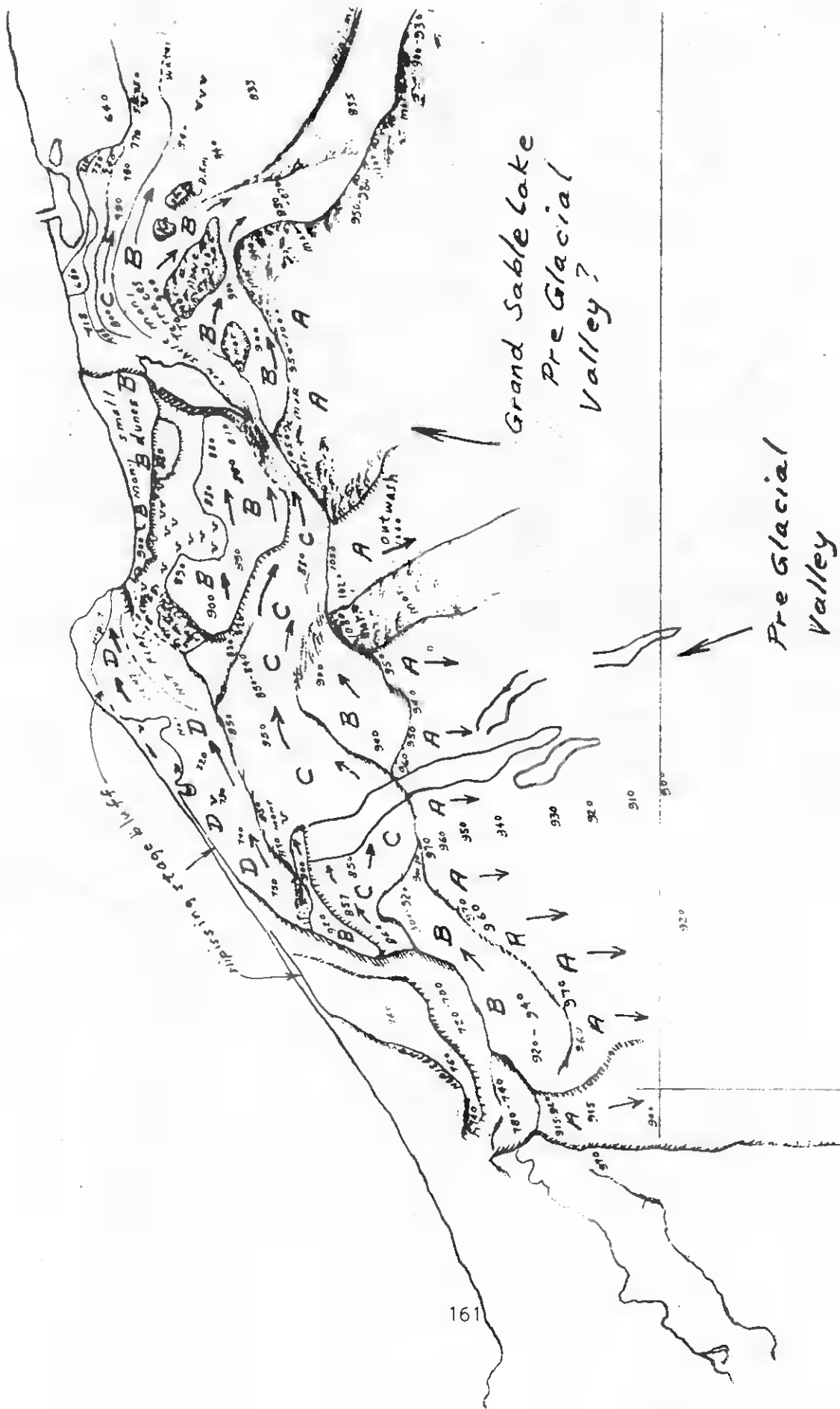
Marginal retreat of the ice from highlands south of Grand Marais allowed still lower outlets to open (Phase III), which resulted in the incision of a channel at 250-253 m, into the Lower Kingston Plain surface. The Hurricane River currently follows this channel. Also at this time, some meltwater spilled southward from the Lower Kingston ice-contact slope south of Beaver Lake, forming the Long Lake Channel. The lower portions of the Kingston Lake Kettle Chain, including Kingston Lake basin must have formed during this phase.

Eventually (Phase IV, and 5 of Blewett, 1994), the ice withdrew to a position several kilometers north of the Lower Kingston ice-contact slope, allowing meltwater drainage across a broad terrace heading at 230 m, known as the Beaver Basin surface. Further retreat of ice allowed even lower channels at 225 and 215 m to be incised into the Beaver Basin surface.

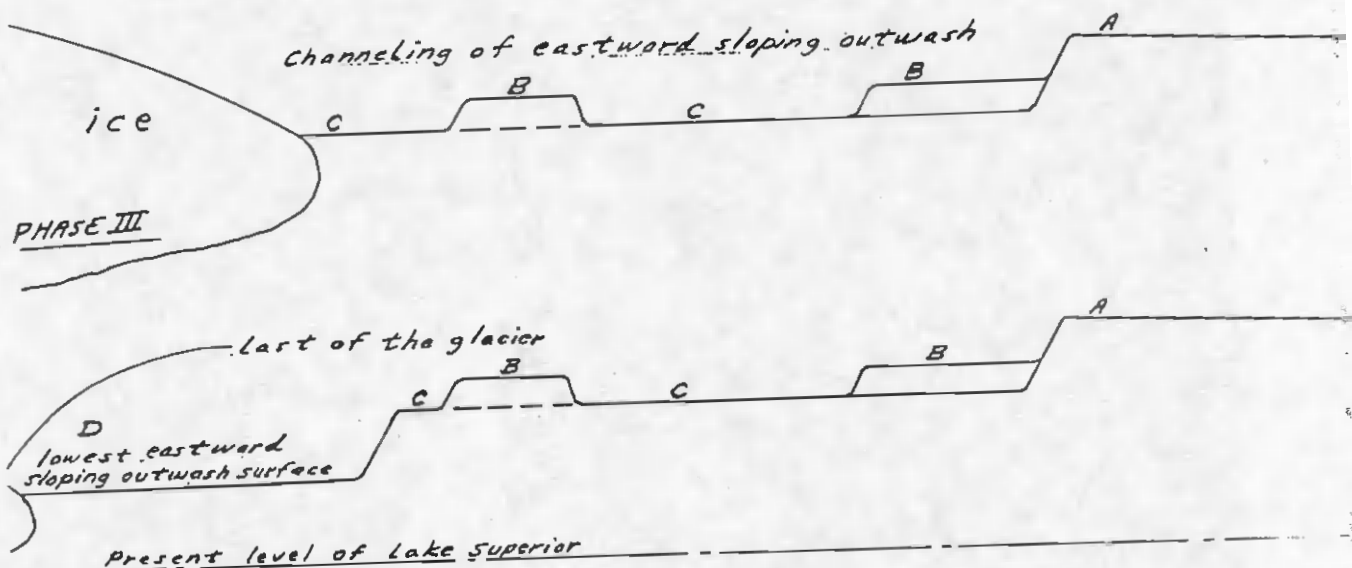
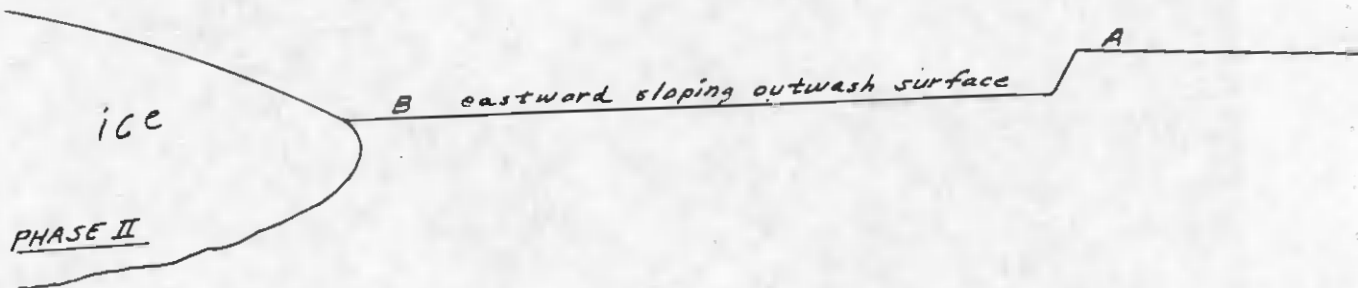
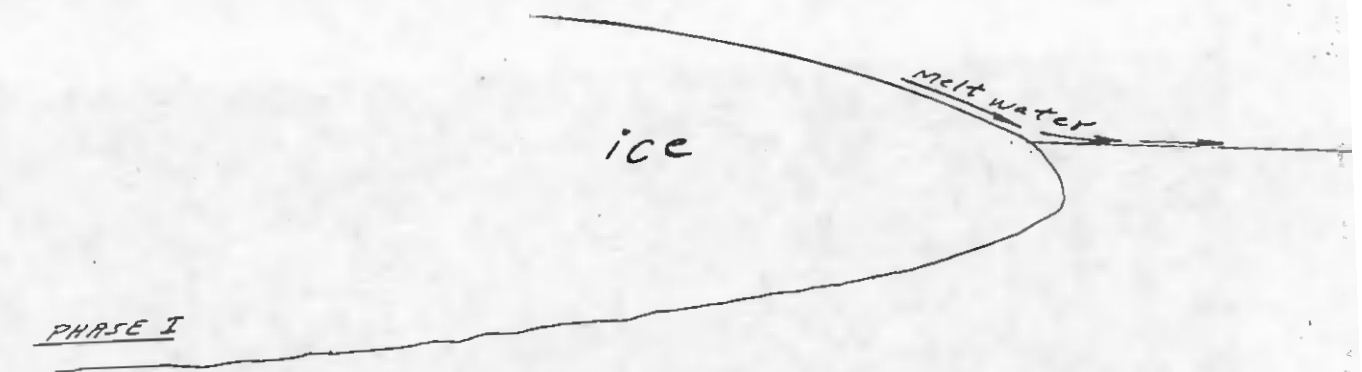
Finally, the glacier retreated to a position just south of Portal Point, but eventually further retreat allowed lake water in the western Superior basin to flow eastward, abandoning the Au Train-Whitefish Channel, into the eastern basin, forming an early version of Lake Minong. Continual retreat allowed Lake Minong to expand, eventually filling the entire Superior basin.



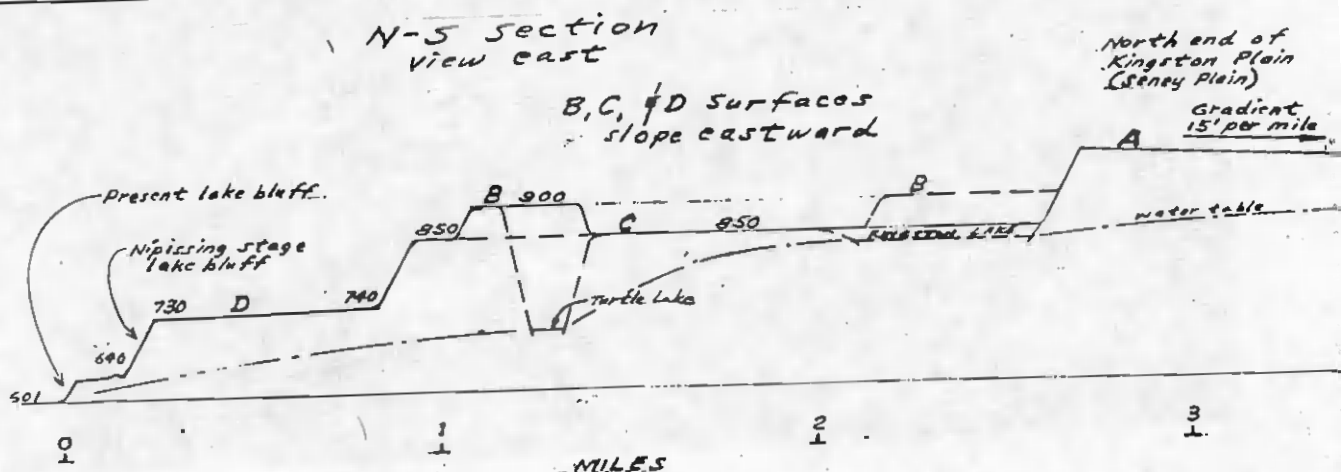
Stops 6 & 7



The Kingston Outwash Plain and meltwater channels near Grand Marais, Michigan

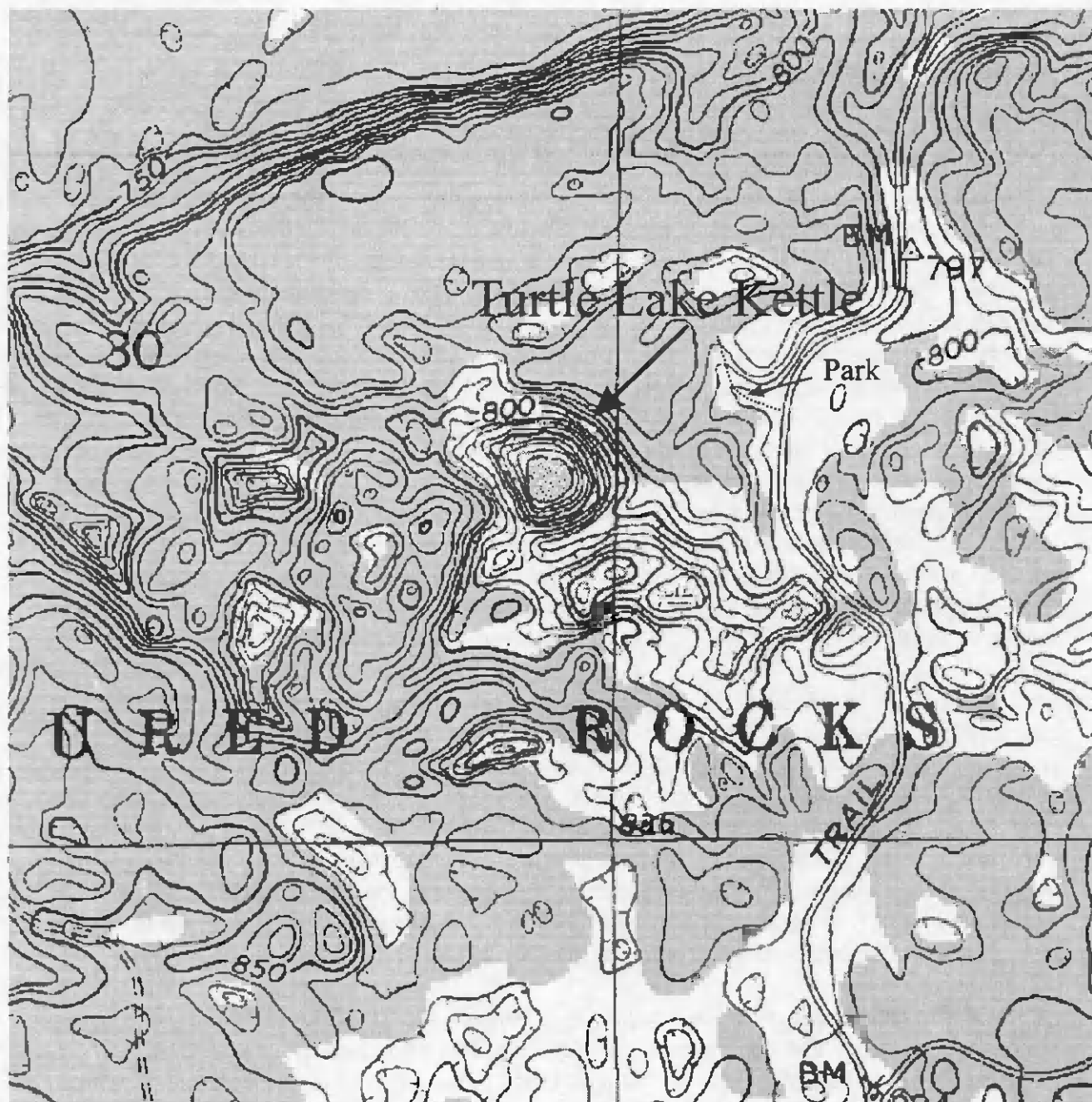


PHASE IV





Mosaic of digital elevation models (DEM) processed to show relief (illumination from SE)



Stop 7. Turtle Lake (actually an unnamed pond, so called on this trip because on previous visits it was observed that many turtles make it their home) occupies a deep kettle in the Kingston Outwash Plain. The kettle is the deepest (though not the largest) in a south-southeast/north-northwest trending chain of kettles that (presumably) were formed as ice stagnated in a now-buried bedrock valley. A seismic study conducted by Regis in the 1980's revealed no reflection from bedrock and a minimum sediment thickness of 60 meters. The kettle is several hundred meters in diameter and is at least 40 meters deep. Because the kettle chain extends across (cuts) each of the outwash and drainage surfaces, the stagnant ice must have been in place from the time the Marquette (Grand Marais) ice was building the upper Kingston outwash surface, and was buried by sediments as the main ice mass retreated. This stop requires a 2-300 m hike through the woods, and if descending into the kettle, a strenuous return hike.

Stop 8. Log Slide

From the Log Slide, the Grand Sable complex is visible to the east. Two geomorphic features, the "Banks" and the "Dunes" are prominent in this view: The Grand Sable Banks consist of a steep, north-facing exposure of glaciofluvial sediments ranging in thickness from 30 to 100 meters, rising directly above the shoreline of Lake Superior. To the south away from Lake Superior, the Banks form a high terrace surface, which is overlain by the Grand Sable Dunes, a dune field "perched" up to 100 meters above the lake and covering about 10 square kilometers. The deposit that underlies the dune plateau, exposed in the Grand Sable Banks, has been variously interpreted as a crevasse filling or kame terrace that incorporated heterogeneous glaciofluvial debris transported by rivers flowing west to east along an ice marginal channel (Drexler, 1981; John D. Hughes, personal communication). Within the central portion of the Banks, stratigraphy of the lower third of the section is obscured by colluvial and aeolian sand; at the east and west ends of the banks, the section is better exposed. Upper portions of the banks are dominated by coarse, cross-bedded sand and include several thin gravel beds. Interbedded silt and sand comprise the middle third of the deposit. The lower third is dominated by fine textured material, primarily silt. A surface gravel layer is presently partially exposed in a "stripped plain" in the central plateau. This layer is often iron-stained and contributes to a lag that periodically armors the bluff crest as the slope retreats southward (Farrell and Hughes, 1985).

The Grand Sable Dunes contain evidence of buried soils, which record episodes of geomorphic change consisting of soil profile development followed by soil profile burial (Anderton and Loope, 1995). In most cases, an entire episode is preserved as a buried soil profile or organic accumulation, capped by relatively finer sediments, such as silt and very fine to fine sand, which is capped by medium to coarse eolian cross-bedded sand. The contact between the upper soil horizon, usually an O/A horizon, is often very sharp, suggesting relatively rapid burial. Such sedimentary and pedological evidence strongly suggests that periods of stability are represented by forest vegetation colonizing landscape surfaces within the Dunes, while periods of instability are characterized by the burial of trees and associated soil profiles and organic accumulations.

A soil catena, consisting of a sequence of buried Spodosols, may be found outcropping in various places throughout the Dunes, especially at the Log Slide locality. The catena, referred to as the Sable Creek Soil (Anderton and Loope, 1995), is traceable across much of the Bluff top and outcrops sporadically within the Dunes reflecting the preservation of a past soilscape which began forming immediately after deglaciation about 10,000 years ago, but was isolated from further surface weathering under eolian sediments beginning about 5000 years ago. The burial event seems to have been initiated by the massive destabilization of the Bank Front during the high lake levels of the Nipissing Great Lakes.

While there may have been some eolian activity immediately following deglaciation, the evidence tends to support the hypotheses of Farrell and Hughes (1985) who suggest that the Grand Sable Dunes are no older than 5500 BP. This is in contrast to Marsh and Marsh (1990) who argue that the Grand Sable Dunes began forming as lake levels rose from the pre-Nipissing lows sometime around 9000 BP. Marsh and Marsh (1990) maintain that sand nourishment to the Dunes increased from 9000 BP to 5500 BP and remained high until around 3500 BP. However, the presence of the Sable Creek Soil, which is developed into glaciofluvial sediments, suggests that the Bluff top was a stable, forested environment from deglaciation until about 5000 BP when eolian sand began to cover the upper surface. Rising post-Houghton levels apparently had little

effect on the Banks until well into the mid-Holocene, suggesting that wave action did not begin to modify the bluff front until lake levels were relatively high during the Nipissing Great Lakes.

Stop 9. Ghost Forest

Subsequent, post-Nipissing fluctuations in lake level also seem to have influenced the Bank front, causing changes in the sediment available for eolian transport on the upper surfaces of the Grand Sables, resulting in a discontinuous occurrence of buried soils and organic layers of various ages within the Dunes. In addition to the major burial event that covered the Sable Creek Soil at least as early as around 4500 BP, radiocarbon dates from the Ghost Forest profile also record a burial event at about 3500 BP and a more recent burial at about 100 years ago. Also a radiocarbon date from other localities in the Dunes suggest that eolian activity also took place at about 1500 BP, and at about 700 years ago.

While, these data may not be conclusive, an analysis of radiocarbon dates from the Grand Sable Dunes strengthens interpretations. Beginning with the investigations of Bach (1978), researchers working in the Grand Sable Dunes have been collecting and radiocarbon dating preserved wood, bulk soil, and charcoal from the study area. In general, the dates seem to roughly delineate major times of increased eolian activity, documenting burial events within the Grand Sable Dunes, and likely recording fluctuations in the lake levels of the Lake Superior basin.

Based on the available data, episodes of increased eolian activity occurred at about 5300, 4600, and 3500 RCYBP, and may also have occurred at about 2500, 2100, 1500, 1000, 500, and 100 RCYBP. The first three episodes seem to coincide well with rising Nipissing, Nipissing I, and Nipissing II phases, which are recognized throughout the southern Great Lakes (Larsen, 1985). The other, later episodes also compare favorably to previous research which indicates fluctuating lake levels in the Lake Michigan basin during the last 3000 years (Larsen, 1985). Larsen (1985) has suggested that Holocene lake level fluctuations are linked to climatic changes that affected the temperature and moisture patterns influencing the water balance of the lakes. Holocene climate changes in the Great Lakes, as revealed by a variety of proxy indicators suggest alternating episodes of cool, moist and warm, dry conditions (Swain, 1978; Bernabo, 1981). Comparison of burial events within Grand Sable system with lake level and climate data from the Great Lakes region for the last 3000 years indicate a general correlation of events. In general, increased eolian activity in the dunes appears to correlate with periods of cool, wet climatic conditions, while periods of relative stability and soil development are associated with times of warm, dry climatic conditions. These findings do not fit Larsen's (1985) model of shore-zone changes during rising and falling lake levels. In the Larsen model, increased precipitation and lowered temperature result in high lake levels that cause tributary stream aggradation, marsh establishment, and soil profile development in eolian sands. Decreased precipitation and raised temperatures cause low lake levels that result in tributary stream erosion, marsh extinction, and soil profiles becoming buried by eolian sands. While Larsen's model seems to work for most coastal areas, perched dunes, such as the Grand Sable system, appear to be reacting differently to climatically-induced changes in lake level.

In general, there seems to have been a nearly constant rain of eolian sediments with relatively short-lived periods of soil development and forest colonization within the Dunes since about 3000 BP. The distinct, buried soil profiles of different ages within the Dunes argues for the fact that only relatively high lake levels are influencing the Bank front. Otherwise, if the Bank front was continually being undercut, there would be no evidence of stability, but rather a

homogeneous deposit of eolian sands. Thus, the evidence of geomorphic changes from the Grand Sable Dunes seems to be an indicator of lake level changes along the south shore of Lake Superior. In sum, the buried soil profiles reflect fluctuations in the amount of sediment available for eolian transport within the Dunes (Farrell and Hughes, 1985). The availability of sediment depends on the condition of the Bank face (Marsh and Marsh, 1987). High lake levels result in increased wave action, which undercuts the bank toe slope, causing mass wasting, destabilizing the Bank face and presenting a fresh surface for wind deflation. If enough sediment is available for a long enough period of time the result is dune development on the high terraces. Low lake levels allow the Bank face to stabilize and perhaps become vegetated, resulting in a reduction or near elimination of available sediment. Thus, dune building on the high terraces is retarded, allowing stabilization and surface weathering to begin, as well as forest vegetation to colonize the fresh landscape surfaces. Thus, soil profiles formed in the Grand Sable Dunes during periods of low lake levels in the Lake Superior basin. These soil profiles and in many cases the forests themselves were, however, buried by eolian sediments, eliminating further soil development and forest growth, the result of high lake levels destabilizing the Bank front.

Stop 10. Sable Falls

At Sable Falls, the Jacobsville Sandstone forms the base of the section exposed in the gorge. The Jacobsville sandstone is a redbed deposit of questionable late Proterozoic-early Cambrian age named by Lane and Seaman (1907) after the Keweenaw Peninsula town of Jacobsville. There, the "Portage Sandstone" that was used as ornamental and construction stone was quarried. It is exposed all along the southern shoreline of Lake Superior from the Keweenaw Peninsula to Munising. However, from Munising to Beaver Bay, it is below lake level, spare for a few occurrences slightly above water. At Sable Falls and south of Grand Marais, good exposures are found. Thickness of the Jacobsville appears to be extremely variable and largely controlled by the underlying Precambrian topography, upon which the Jacobsville rests unconformably for the most part. For example, Hamblin (1958) cites an instance of a 2 wells, one of which drilled through 1100' of Jacobsville Sandstone, and the other well drilled through only 46' of the same rock before reaching Precambrian quartzite, and the wells are only 10 miles apart (T47N, R1E).

The Jacobsville can be easily recognized by its striking red to red-brown color. Much of the Jacobsville is mottled with white reduction splotches and streaks. The color change is abrupt and distinct. Most of the mottles are related to variations in permeability of the beds. That is, where the beds have the greatest permeability, leaching and white coloration is the greatest. Most fine grained beds and shale lenses in the Jacobsville are not leached at all. Leaching most often follows bedding planes, fractures such as joints, and cross-bedding. Spherical spots of leaching appear to be controlled by a dark grain or pebble at occurs at the center of the spots. The grains are probably of some lithology that have a composition sufficient to produce a reducing environment.

Texturally, the Jacobsville Formation ranges from conglomerate to a fine grained siltstone. The formation has 4 different facies, as described by Hamblin (1958). The conglomerate facies occurs mostly at the base of the formation, especially where it lies unconformably on Precambrian rocks (Presque Isle near Marquette, for example), but may also be found scattered throughout the younger beds. Thickness of these beds can be as great as 5 meters. The most common of the 4 facies (laterally and vertically) is a red to reddish brown, medium-grained, lenticular bedded sandstone. In some places, lenticular bedded sandstones are

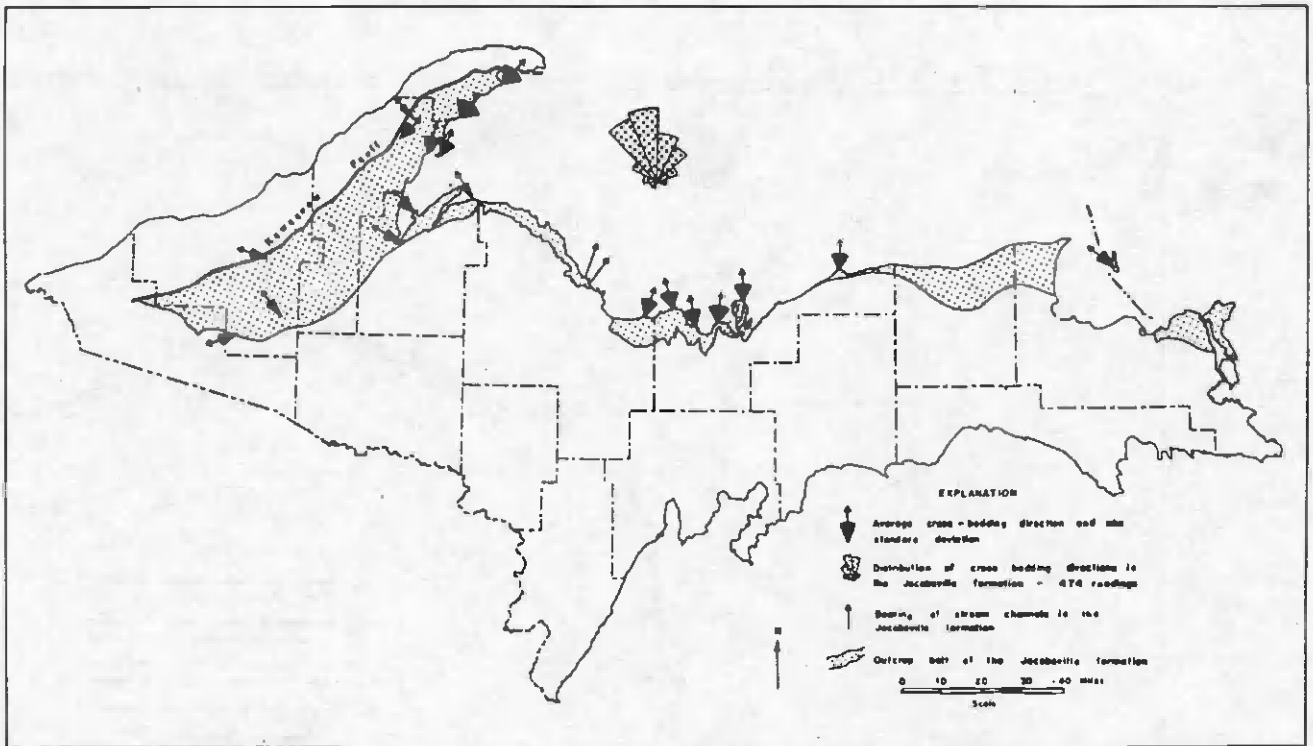
over 100 meters in thickness. Trough cross bedding and ripple marks are common in this facies. Selective leaching along cross bedding in the formation accentuate the structures. The occurrence of ripple marks, mud cracks and clay pebbles clearly indicate a fluvial environment of deposition. A massive facies of the Jacobsville is characterized by persistent, thick beds of relatively structureless sandstone, many over 3 meters in thickness. At Victoria Falls, a measured section of 200 meters of Jacobsville consists almost entirely of 3 meter thick beds of sandstone. Some laterally persistent oscillation ripple marks are found in the beds and support a lacustrine environment of deposition. Finally, Hamblin recognized a red siltstone facies. Though not common (except at Laughing Fish Point and Agate Falls), beds of siltstone and shale occur interfingering with other facies and is interpreted as a quiet-water lacustrine environment of deposition.

Paleogeographically, the Jacobsville Sandstone represents a continental red bed sandstone deposited by streams flowing northward from the Northern Michigan highlands. As shown in the paleocurrent (cross bedding and ripple marks) map produced by Hamblin (1958) there is very little deviation in trend (of indicators) from the mean.

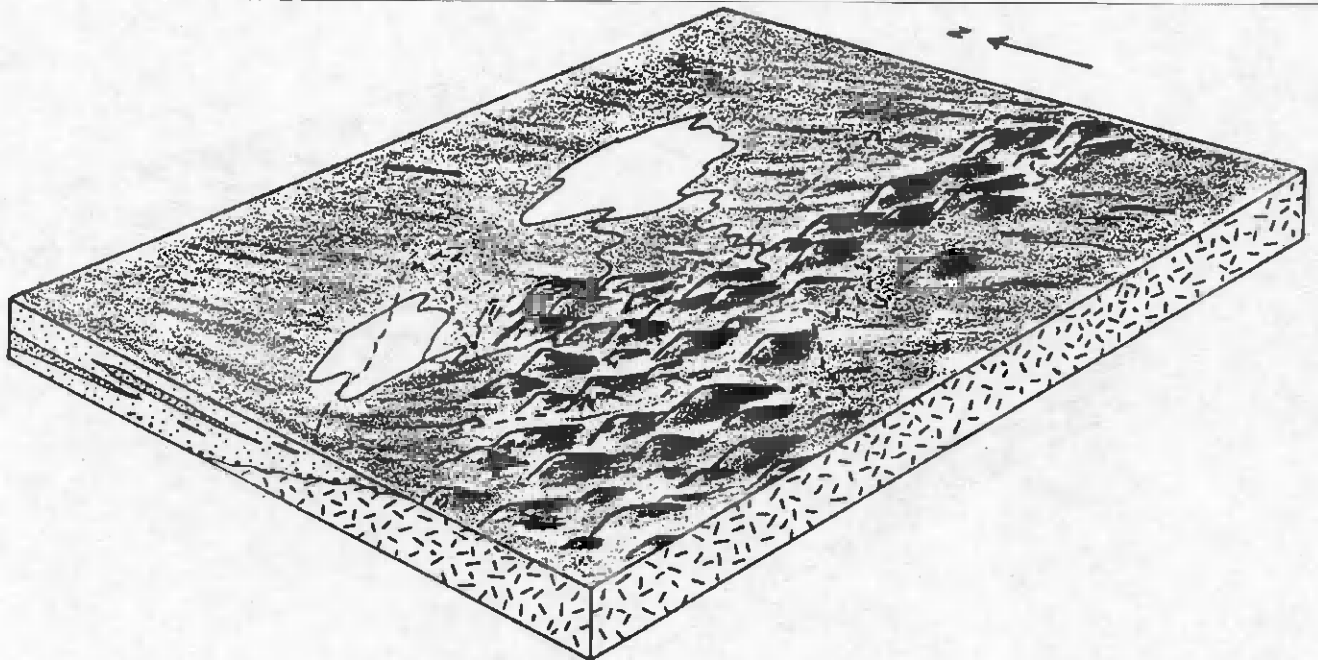
An unconformity, in some places a disconformity, but as on Grand Island, an angular unconformity, separates the Jacobsville from the overlying Chapel Rock Member of the Munising Formation. At Grand Island the Jacobsville dips a few degrees northward, and the Chapel Rock member of the Munising Formation dips a few degrees southward, but at this stop, bedding appears to be parallel or nearly parallel at the contact.

The lower two to fifteen foot section of the Chapel Rock member is a basal conglomerate, 90% vein quartz, quartzite and chert with lesser amounts of slate, basalt, granite, iron formation and sandstone. The upper 49 to 60 feet is pink to light buff to brown, medium grained orthoquartzitic sandstone with several thin, blue-clay and silty shale beds. The beds in the top 20 or 40 feet are moderately or very dolomitic and frequently "burrowed." Limonite imparts a light yellow-gray color to the member and occasionally red to some thin beds.

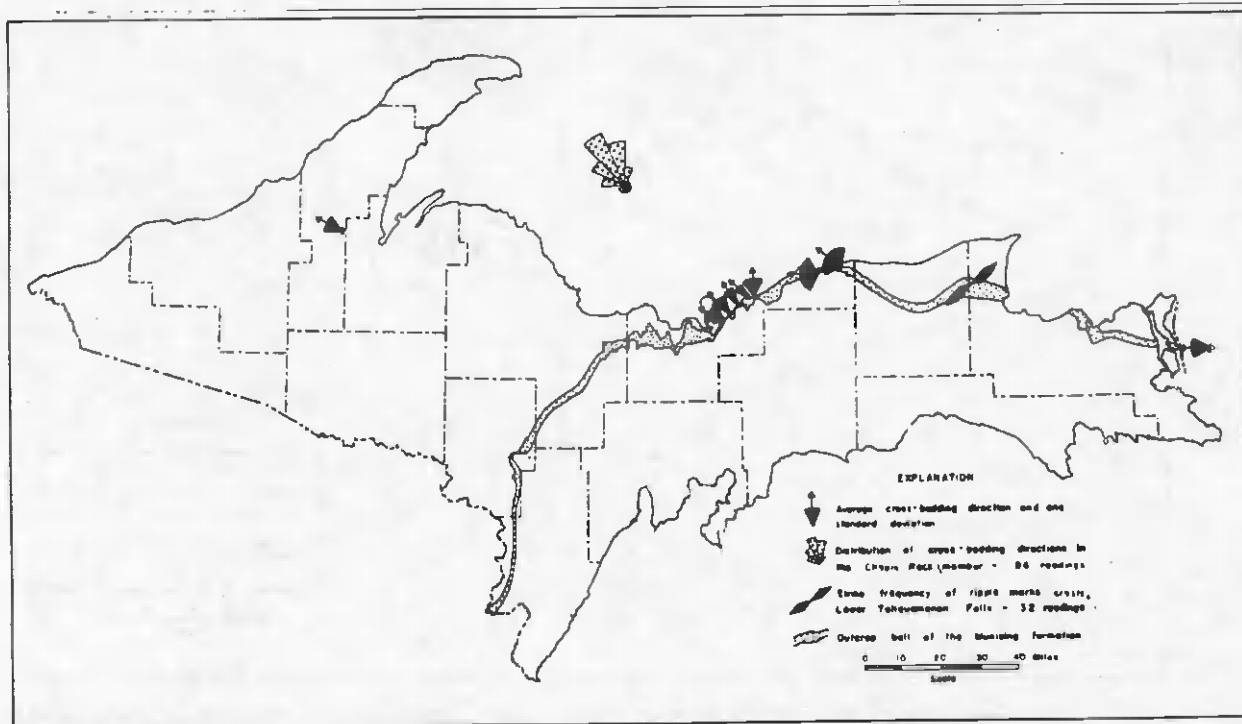
The (lower) Chapel Rock member represents a period when the Northern Michigan Highlands (to the south) were eroding and shedding their sediments into a shallow epicontinental sea to the north (see the figures on the next page). The Chapel Rock member is composed almost entirely of quartz (mostly of igneous origin; Hamblin, 1958) with minor amounts of feldspar. Heavy minerals in the member include well-rounded grains of tourmaline, and abundant zircon (20-50% of the total heavies, both altered and unaltered), magnetite, hematite, and ilmenite. Silica is the predominant cement in most places and occurs as secondary overgrowths of varying degrees. Farther east, near Tahquamenon Falls, porosity in the Chapel Rock member is reduced to almost zero due to the silica cement. Texturally, the Chapel Rock member is well-sorted, medium-grained sandstone. Most grains are 1/4 to 1/2 mm diameter. Color gradually ranges from white to buff to red. Large scale trough cross bedding is the most abundant sedimentary structure in the Chapel Rock member. The size of these troughs range from 1 to nearly 200 meters in width (mean about 10 meters). Megascopically, they are useful for differentiating the Chapel Rock Member from the underlying Jacobsville Formation and the overlying Miners Castle member. At Miners Castle, they are abundant. They represent deep erosional channels that were cut into the older units. Near the base of the Chapel Rock member, pebbles become abundant in the cross-beds that fill the troughs. Hamblin (1958) suggests that they are indicative of marine deposition in embayments along a cusped shore. Ripple marks are less abundant and are both current-formed and oscillatory. Where current-formed, they indicate a mean transport direction to the northwest with little standard deviation about that mean (see figure illustrating cross-bedding directions in the U.P.). This indicates a fairly steep gradient with little



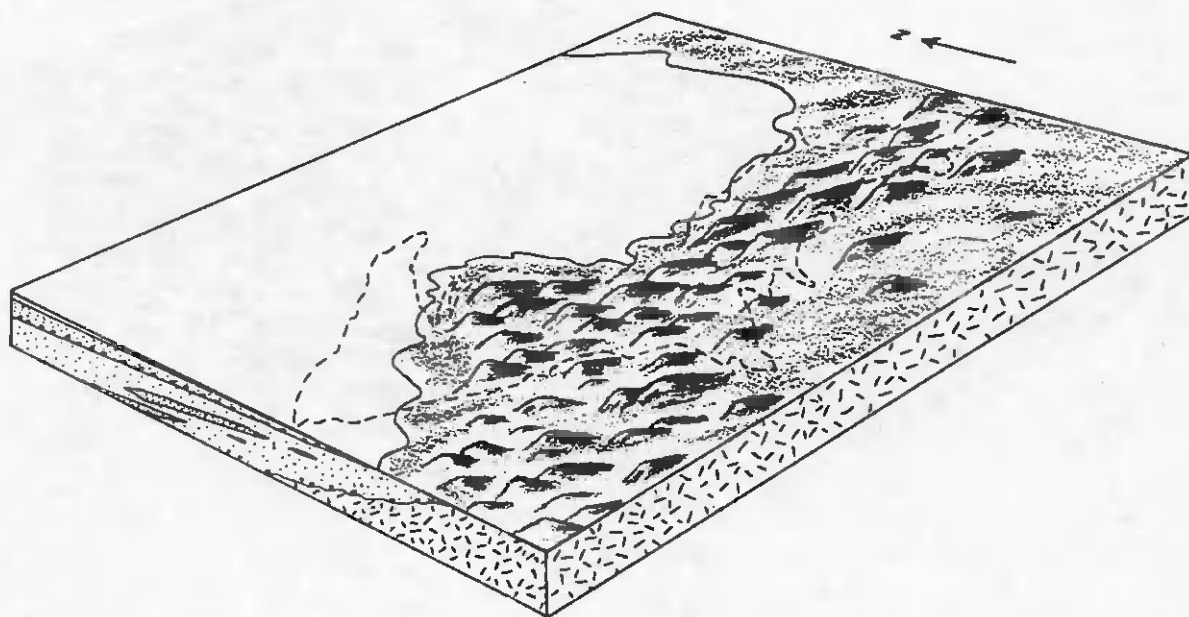
Cross bedding directions in the Jacobsville Sandstone (after Hamblin, 1958)



Paleogeography during deposition of the Jacobsville Sandstone (after Hamblin, 1958)



Cross bedding directions in the Chapel Rock member of the Munising Formation (after Hamblin, 1958)



Paleogeography of Northern Michigan during deposition of the Chapel Rock member of the Munising Formation (after Hamblin, 1958)

meandering. In the upper part of the Chapel Rock member, mudcracks are found in the fine-textured sandstone and the shale beds. They are about 5 cm in diameter and the intervening cracks are filled with sand. Paleogeographically and environmentally, they indicate deposition in a shallow water, subaerial environment with the sea regressing northward. These beds grade directly into the Miners Castle Member and suggest a minor regression of the Chapel Rock sea.

Compact till is found overlying the bedrock in this valley. The till is reddish in color, and texturally ranges from clay to cobbles. It is likely Marquette age (about 10,000 YBP) and was deposited as the Munising moraine and Kingston outwash plain were being deposited (Phase 1 of the previous diagrams).

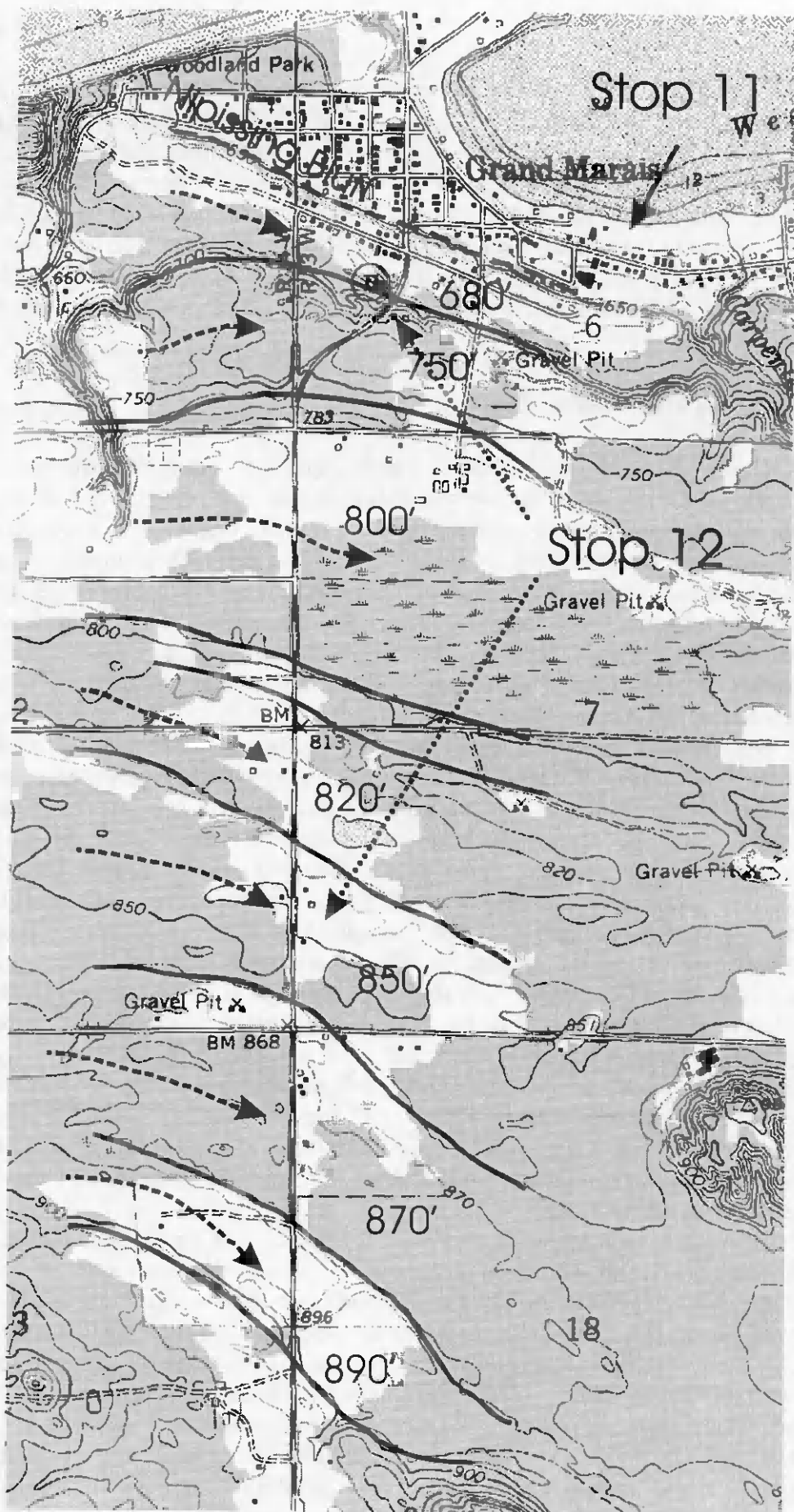
Stop 11. Grand Marais Harbor

Grand Marais Harbor is the only Harbor of Refuge between Marquette and Sault St. Marie. Originally, the protected bay was a summer camping place for Native Americans. Later, French voyageurs used the bay as stopping place to either prepare for, or recuperate from, the dangerous paddle along the cliffs of the Pictured Rocks during their travels along the south shore of Lake Superior. The town itself was established in the 1860's by the fishing and lumber industries as a boom town. However, by 1910, the lumber industry declined and Grand Marais became mainly a commercial fishing port. Eventually, this industry also declined and the community became all but a ghost town. Today, Grand Marais is seeing a renaissance as a summer and winter recreation town.

Recent, soon-to-be-published research at the Drexler-Carter (D-C) site (Anderton, in progress), a paleo-valley fill section exposed along the front of the eastern portion of the Grand Sable Banks, suggests that prior to the Nipissing transgression, the Grand Marais area may have consisted of extensive lagoon. Evidence for the lagoon consists of extremely thick. Compressed peat deposits, dated at between approximately 7000-6000 BP, which have been found at the D-C site, on the floor of Grand Marais Harbor by divers, and during drilling of wells to the east of the Harbor. The pre-Nipissing lagoon was likely protected behind an extremely large bay barrier, which may have extended from as far west as the ancestral Grand Sable Banks or Au Sable Point. The high ground and associated dune forms, which begin at Lonesome Point and extend to the east for several kilometers, may be remnants of this older barrier, which was apparently breached during rising Nipissing levels. Much further work is needed to verify these interpretations.

The Nipissing transgression inundated the Grand Marais area, flooding the mouth of the Sucker River and extending inland for several kilometers south of the high ground that begins at Lonesome Point. Steep, Nipissing-age, wave-cut bluffs at an elevation of about 195 m (640 ft) rim the southern edges of the town and harbor. Much of the town appears to have been built on a Nipissing wave-cut platform.

Recently, Grand Marais Harbor has been the focus of a great deal of concern by local residents in regard to the condition of West Bay. From the time of the earliest written records and maps of Grand Marais, the bay was originally portrayed as relatively deep water lagoon, protected behind a low, sandy baymouth barrier that extended from the west side of the current town, east to Lonsome Point. A small channel, which allowed water to pass from the bay into the waters of lake Superior, provided the only navigable entrance to the harbor. This natural channel, adequate for several centuries for Native Americans and Voyageurs in canoes, was prone to sand bar development, which interfered with commercial shipping associated with the lumber and fishing industries that began in the late 1800's. Consequently, various harbor protection structures, including eventually a large breakwater, were built beginning as early as



Eastward-sloping meltwater discharge channels south of Grand Marais

1883 to stop sand bars from blocking the entrance to the bay (USCOE, 1980).

Over the years, the harbor protection structures have effectively blocked coastally-transported sand, that would have otherwise been conveyed by littoral drift processes, from replenishing the eastern portion of the original barrier. Consequently, this part of the barrier has been removed by wave erosion, exposing nearly the entire east end of the bay to Lake Superior. On the west side of the structures, sand eroded from the Grand Sable Banks and transported to the east has been deposited. Since 1961 the beach in this area has been growing at a rate of 38,000 cubic m per year (USCOE, 1980). According to Marsh (1990), the beach has widened by 2500-3000 m, and, if left unchecked, will eventually widen to the point where the beach effectively cuts off wave-contact with the Grand Sable Banks. If this happens, the sand supply to the Grand Sable Dunes, which is ultimately tied to lake levels and bluff recession, will be artificially reduce dune nourishment rates. In effect, the Dunes may cease to exist.

Stop 12

Stop 12 is not really a stop, but an overview of channels as we leave Grand Marais southward on M-77. Eastward discharging streams cut channels at successively lower elevations as the Marquette (Grand Marais) ice retreated into the Lake Superior basin. At least 8 channels are recognized from 207 meters to 271 meters. Leverett (1929) and others mistakenly interpreted these surfaces as Lake Algonquin wave-cut platforms. Hughes (1968), through use of aneroid barometers and topographic maps, determined they slope eastward and asserted that they are glacial spillways. Further, Hughes recognized the fact that, in profile, the surfaces actually slope southward toward the next escarpment (characterized by poorly drained swampy regions at the south edge of the surfaces). If they were wave-cut terraces, the slope in profile would be in the opposite direction.

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