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Part 2 – FieldTrip Guidebook

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Cover Photo: Brecciated banded iron formation from Ishpeming, MI. This photograph is similar to Plate XXV in Van Hise, Bayley, and Smyth, 1897, U.S. Geological Survey Monograph 28 "The Marquette Iron-Bearing District of Michigan." (photograph by Tom Waggoner)

54TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

PROCEEDINGS VOLUME 54 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

- **TRIP 1:** BANDED IRON FORMATION OF THE MARQUETTE DISTRICT
- **TRIP 2:** ARCHEAN-PALEOPROTEROZOIC UNCONFORMITY AT SILVER LAKE—SEISMITES FROM THE SUDBURY IMPACT?
- **TRIP 3:** GEOLOGY OF THE BACK FORTY PROJECT
- **TRIPS 4 AND 8:** GEOLOGY OF THE EAGLE PROJECT
- **TRIP 5:** THE SUDBURY IMPACT LAYER AT THE MCCLURE LOCALITY
- **TRIP 6:** SUSTAINABLE RECOVERY OF IRON FROM THE MARQUETTE DISTRICT
- **TRIP 7:** GEOLOGY OF THE KEWEENAWAN BIC INTRUSION

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Field Trip 1

BANDED IRON FORMATION OF THE MARQUETTE DISTRICT

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The absence of evidence is not
Evidence of absence

Carl Sagan

BANDED IRON FORMATION OF THE MARQUETTE DISTRICT

This two day field trip within Marquette County will concentrate on the distinct types of iron deposits and clues to their formation. The trip will include both active and idle mining sites and outcrop locations never included in any prior field trip of the Marquette iron range. Cleveland-Cliffs will open their mines for the group. This field trip guide will include a narration of the overall Proterozoic geology of the Marquette Range. All Figures and Tables denoted with capital letters are part of the text. All figures denoted by a small "f" are found on the accompanying CD where full color will enhance their value in the discussion The CD also has plan geology maps of each of the stops and a photo gallery of old mining pictures taken throughout the history of mining on the range. Trip stops will include examples of banded magnetite, hematite, carbonate, silicates, clastics), hard ores (microplaty, specularite, magnetite) and supergene oxidation with enrichment. We will visit several examples of silica/hematite vents along with examples of hydrothermal alteration. We will also examine the late non ferrous metal overprint on the Negaunee iron formation.

Acknowledgements

I would like to thank Cleveland-Cliffs Inc. for reproducing the plan geology map of the Marquette range and for permission to attend their operations on the range. Appreciation is also expressed to all of Cliff's personnel including Glenn Scott, Helene Lukey and Al Strandlie who helped on the field trip and in moving the drill core for examination during each day's lunch session. USX is also acknowledged for allowing access to their Champion property The old photos presented in the CD have been graciously contributed by Cleveland-Cliffs, Jack Deo of Marquette, the Michigan Iron Industry Museum and the State Archives of Michigan. Both the Iron Industry Museum and the Cliffs Shaft Museum are acknowledged for hosting a lunch session on each of the field days. Thanks also go to the City of Negaunee for hydraulically cleaning outcrops in the area of the Jackson Mine. I am also indebted to John and Gretchen Klasner for their patient editing of the field trip guide.

MARQUETTE RANGE SUPERGROUP

Paleoproterozoic strata of the Marquette Range Supergroup (MRS) lie within the Marquette and Republic troughs that formed within the Archean basement (see plan geology foldout map). The three Groups (i.e. Chocolay, Menominee and Baraga) are related to plate tectonic activity associated with the Penokean and younger plate tectonic events (Schulz, 2007). They were drap-folded and faulted into the underlying troughs in the basement forming the gently west or northwest-plunging Marquette and Republic synclines respectively. The Chocolay Group includes a basal conglomerate overlain by quartzites, carbonates and slates. The Menominee group contains alternating slates and quartzites with a limited banded iron formation overlain by the economically significant Negaunee iron formation. The stratigraphic column includes the Hemlock Volcanic formation from the Amasa Oval where an overlying iron formation was emplaced at the close of volcanic activity. An unconformity separates the iron formation from the overlying Baraga Group.

Chocolay Group
Enchantment Lake Formation

This group was named by Gair and Thaden (1968) for a sequence of conglomerate, greywacke and slate found at the eastern end of the Marquette Syncline. It lies on Archean basement or Mesnard quartzite. It has been described as lenticular by Gair (1975) who felt it was missing over topographic highs in the older terrain. The thickness of the basal unit varies from 0 to 600 feet. The unit correlates with the Fern Creek found in the Menominee and Felch Districts. In the Marquette area of the Animikie basin the earliest unit is a fairly thin sequence of conglomerate with minor sandstone and shale. The conglomerate contains clasts of the underlying local Archean terrain indicating limited movement of the clasts. Interpreted dropstone evidence convinced Pettijohn (1943), Gair (1975) and Ojakangas (2001) to conclude the unit was deposited in a glacial environment. However, Bayley et al., (1966), Gair and Thaden (1968) and LaRue (1980) favored an alluvial fan depositional environment. Van Hise and Lieth (1911) noted that the composition of the conglomerate is a function of the underlying rock upon which it rests.

The conglomerate in section 22, T. 46 N., R. 26 W. consists of salmon colored cobbles or boulders (fig. 1). In the SE, NE, section 22, T. 47 N., R. 26 W. abundant octahedral and platy hematite replacing fine detrital grains found between the pebbles (fig. 2). Gair (1975, p.17 & 18) noted elevated potassium and sodium values for the slate component indicating that fluid influx caused the alteration.

Mesnard Quartzite

This unit was named by Van Hise and Bayley (1892) for the prominent outcrop in the Harvey area. The massive white vitreous quartzite attains a maximum thickness of 500 feet. It contains numerous ripple marks (fig. 3) and clasts and in places exhibits cross bedding. It is present only in the eastern half of the Marquette trough and has not been identified west of section 31, T. 48 N., R. 26 W. The predominant color of the well sorted quartz (+90% silica) is white. Numerous quartz veins and veinlets are common and some contain specular hematite. The unit is believed to be equivalent to the Sunday quartzite on the Gogebic Range, the Sturgeon quartzite on the Menominee Range and the Pokegama quartzite on the Mesabi Range.

Kona Dolomite

The major Kona outcrop area is on the eastern end of the Marquette syncline. The unit is not present in the central and west portions of the trough either due to faulting or non deposition.

The Kona formation consists of dolomite (48%), argillite (42%) and quartzite (10%). The argillite was originally siltstone, mudstone or clay stone. Thickness of the unit varies between 0 and 800 meters. Pastel colors of cream, buff, pink, orange, salmon, tan, maroon, and purple characterize most of the carbonate series. The argillite is gray, green, tan, orange and chocolate brown. The quartzite exhibits shades of white to pink (fig. 4) to red. Minor brown chert beds are also observed. Bedding thickness varies from one centimeter to five centimeters. Some dolomites exhibit oolites. Quartz grains both in the dolomite and quartzite average .05 mm while the grain size of the dolomite averages .3 mm with some dolomite beds containing a uniform coarse crystal size that averages .25 cm.

The Kona has been correlated with the Randville dolomite on the Menomonee Range and the Amasa uplift area. It is also correlated with the Bad River dolomite on the Gogebic Range based on its relative position in the stratigraphic column and the absence of dolomites in general in the younger sediments throughout the entire Lake Superior area. The Kona has many similarities to portions of the Lorraine formation north and east of Sault St. Marie, Ont.

Taylor (1972) (Figure 1) identified eleven units that make up the Kona formation. His work helped to identify the distinctive members that in turn helped to resolve the structural movement along faults.

Detrital quartz appears to originate from the south. The source direction of detritals for the younger iron formations is again shown to originate also from the south. Ripple marks (fig. 5) and other sedimentary features suggest a shallow or shore line environment.

Bladed or fibrous rosettes of chert, irregular nodular quartz and cubic to rectangular bright red dolomite crystals indicate replacement of gypsum, anhydrite (fig. 6) and halite (fig 7). These occur in both the dolomite and pelitic sequences.

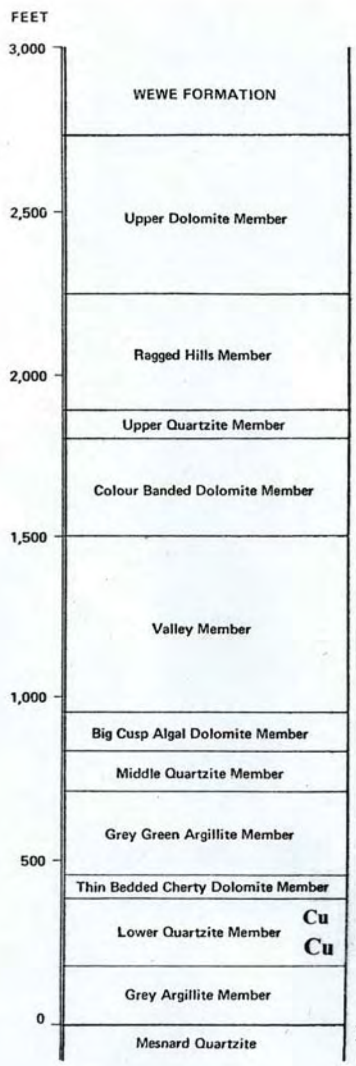

Figure 1

Kona Dolomite Member Subdivision After Taylor (1972)

Styolites can commonly be found between sedimentary units. Episodic super saturation could have caused the precipitation of the salts.

There is abundant evidence of early life preserved in the Kona primarily in the form of stromatolites. These can be very large bioherms of the colleria type (fig. 8) or small thin undulating or corrugated mats (fig. 9) that have been replaced by silica and tend to weather out into thin wafer zones in the dolomite. Sharks Bay in Western Australia currently contains sub tidal stromatolites that grow under hyper saline conditions.

Detail mapping utilizing known stratigraphy has confirmed a number of east-west striking high angle (75^{o} to the north) normal faults with north side down parallel to the main syncline axis. The eastern terminus of the Marquette trough in the Harvey area appears to be a north-south flexure with the Proterozoic sequence being present to the east of Harvey under Lake Superior.

Airborne magnetic data suggest a synclinal structure plunging to the east under the lake to the Keweenawan Rift hinge line east of the City of Marquette.

Neither soft sediment slumping nor tectonic folding is prevalent in the Kona. Metamorphism, where it exists, is the low greenschist facies and lies within the chlorite zone (James, 1955). Intraformational brecciation is common (fig. 10) and may reflect a local tectonic event (Bayley et al, 1966) or could be due to a collapse in a supratidal environment (Larue, 1981). Isopach maps of six Kona members (Taylor, 1972) clearly illustrate a general thickening of the trough centering on section 6, T.47 N., R. 25 W. By the time the Negaunee iron formation was formed the largest basinal down warping had shifted southwestward to section 19, T. 47 N., R. 26 W.

The general plunge of the Marquette syncline is to the west. The north side of the syncline exhibits a steep dip to the south with only minor north-south fault offsets. The south and southeastern areas exhibit domal flexures and complex fault offsets. A number of near-vertical, basic, fine-grained dikes (fig. 11) cut the Kona. Most are now primarily chlorite in composition. In addition there are abundant veinlets and joint fillings composed of quartz, carbonate, microcline and tourmaline.

The Kona hosts strata bound copper sulfide resources, which have attracted exploration interest dating from 1888. Copper sulfides are found as disseminated grains, grain aggregates and shear zone fillings (fig. 12 & 13). Both vertical and lateral sulfide zonation have been identified. Over a 10 mile distance the sulfide assemblage shows a decrease in copper from east to west (Table 1).

Table 1 Copper Assemblage of the Kona Dolomite from West to East

WEST	pyrite--------	pyrite---------	chalcopyrite-----	bornite-------	chalcocite	EAST
		chalcopyrite	bornite	chalcocite	pyrite	
			pyrite	pyrite		

Taylor (1972) suggested the copper was deposited in a Sabka environment involving connate waters that carried and deposited sulfides in a reducing environment. Since there is no evidence of a reducing environment existing at anytime, this is not a particularly appropriate process for the deposition of the Kona sulfides. An alternate source could be progressive hydrothermal precipitation much like that which occurred at White Pine. However, the only other alteration is silica flooding which does not follow the sulfides. The silica does carry specular and micaceous hematite. A resource of half a billion short tons of argillite/quartzite containing about 1% copper has been indicated. In addition to the copper mineralization there are concentrations of microplaty to specular hematite (fig. 14), the significance of which will be further discussed in the section covering the Negaunee, iron formation.

The abundance of carbonate, algal features, psuedomorph quart/chert after evaporates, weathering, ripple marks and mud casts suggest a shallow lagoonal to open tidal environment with hypersaline water subject to intermittent subaerial exposure. Further, a warm to temperate climate is most likely to have accompanied this environment.

Wewe Slate

The Wewe occurs only on the eastern end of the Marquette Syncline and does not have an equivalent anywhere else in the Paleoproterozoic Lake Superior Basin. The unit is characterized as a green-gray-black, fine grained, faintly-laminated or banded fissile argillite. The major components are quartz, sericite and chlorite. The thickness ranges between 400 and 3000 feet. Some zones contain 2-5% pyrite as disseminations, cubes or concretions and contain the occasional calcite veins. Outcrops are too limited to define the internal stratigraphy but existing diamond drill holes would provide an excellent basis for developing the detailed stratigraphy.

Menominee Group

Ajibik Quartzite

The Ajibik is a generally white vitreous quartzite with some graywacke components. It lies uncomfortably over the Wewe and is in turn conformably overlain by the Siamo slate. A basal conglomerate occurs in many places around the Wewe Hills uplift. Gair (1975) noted in section 23, T. 47 N., R. 26 W. that the basal conglomerate contains jasperoid (silicified Kona dolomite) and clasts of andalusite/chloritoid schist suggesting some of the hydrothermal alteration occurred prior to formation of the conglomerate. The north end of the quartz/hematite stockworks transects the Ajibik and caused brecciation in the Ajibik. It suggests the linear stockworks zone was relatively long lived starting before the Ajibik and lasting until after the Negaunee Iron formation. The thickness of the Ajibik ranges from 450 to 600 feet.

Siamo Slate

Rock types included in this formation are slate with lesser feldspathic quartzite and graywacke. Both chlorite and sericite are locally abundant. The first iron formation that occurs in the Marquette trough is the Goose Lake member which is up to 100 feet in thickness. It can be traced via outcrop and magnetics for at least 5 miles on the south and east side of the trough.

Gair (1975) identified several lithologic sub units within the Siamo: lower laminated slate, Goose Lake iron member, middle slate, quartzite/graywacke and supper slate with chert bands near the top. The transition to the overlying Negaunee is gradual.

The Goose Lake member was named by Tyler and Twenhofel (1952) for the banded-laminated iron formation which is primarily siderite, chert with minor magnetite, chlorite and stilpnomelane. Phosphorus values are four times higher than those found in the Negaunee. The Siamo ranges in thickness from 1000 to 3100 feet.

Outcrops of the Goose Lake can be found along the shoulders of M-35 just northeast of the Empire Mine in sections 15, 16 and 20 T. 47 N., R. 26 W.

Negaunee Iron Formation

The Negaunee iron formation has been the focus of economic exploitation since its discovery in 1844. Early mining concentrated on the hydrothermal hematite and magnetite ore (hard ores) that outcrop at surface on topographical highs. Later during the 1800s shallow supergene enriched hematite (soft ores) deposits were brought into production via underground mining methods. By the middle of the 1900smost of these deposits were depleted. Throughout the period of hard and soft ore production, significant tonnages of banded iron formation were mined and shipped as siliceous ore that was used in the furnace operation to provide adequate slag production. During the 1950s concentration schemes were applied to the banded iron formation to produce an iron concentrate/pellet with relatively low silica and superior physical and chemical characteristics that improve furnace productivity.

The Negaunee iron formation is one of many iron formations that occurs in the much larger Paleoproterozoic Animikie basin and whose remnants can be found around Lake Superior in Wisconsin, Minnesota, Michigan and Ontario. The collective iron deposits became known as the Lake Superior Type (LST) as opposed to the smaller Algoma Type. A comparison of LST and Algoma Type features of banded iron formations (bifs) (Table 2) would suggest more difference than actually exists. The argument that LST lack an igneous association is not valid. The Animikie basin contains some very extensive extrusive rocks in the form of the Clarksburg, Hemlock and Emperor volcanics. Similarly, bifs in both Western Australia and S. Africa contain many tuff intervals (called shales) within the iron formation (LaBerge, 1966, 1966).

Table 2
Features Common to LST vs Algoma Type BIF

LST	Algoma
low igneous association	direct igneous association
1.8-2.4 b.y.	+2.5 b.y.
rifting environment	volcanic arc environment
low S, Na, K, Al, P	higher S, Na, K, AL, P
higher CO2	lower CO2

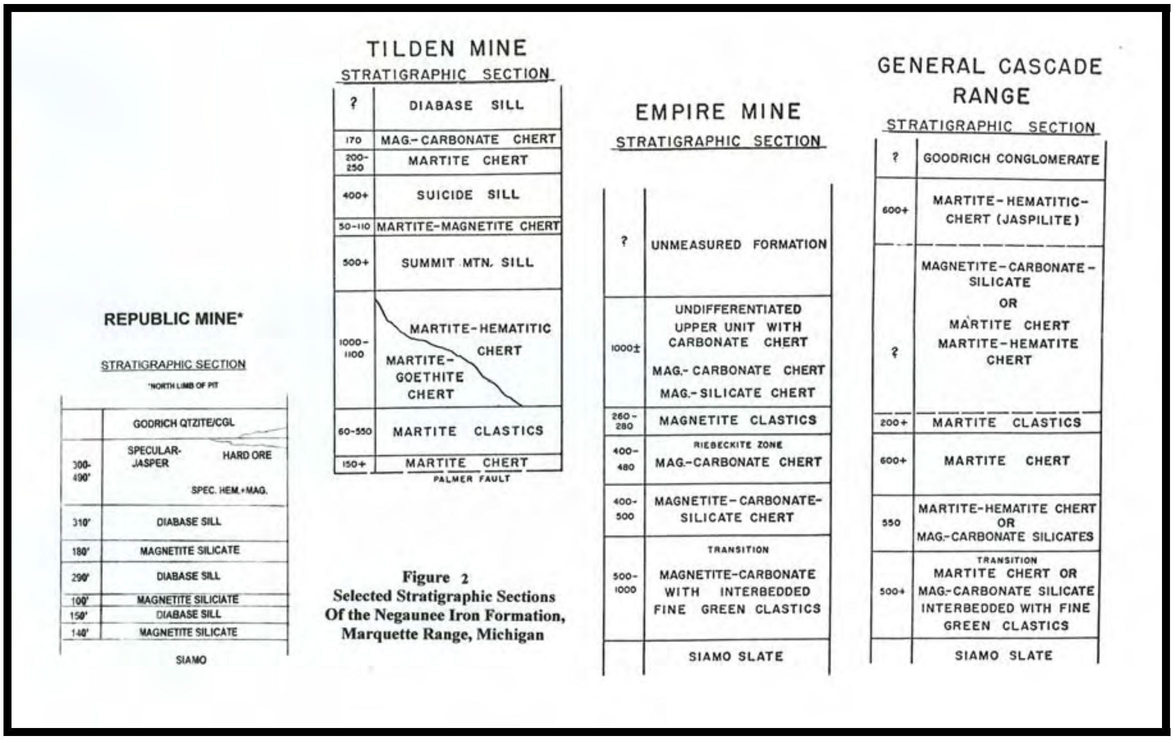

Figure 2
Selected Stratigraphic Sections
Of the Negaunee Iron Formation,
Marquette Range, Michigan

More recent exploration worldwide has identified large iron formations in the Sokoman in Labrador, the Hamersley and Nubbaru in Australia, the Minas Gerais and Carajas in Brazil, the Kuruman/Griqualand deposits in South Africa and the Krivoy Rog in the Ukraine.

It has long been debated as to whether the Negaunee is a time equivalent to the Biwabic, Gunflint, Ironwood, Fence, Riverton and Vulcan. Recent work on defining the existence and position of the Sudbury ejecta (Cannon, 2007) has established that these iron formations are essentially time equivalents. It also indicates the iron formation is older than 1850 Ma and slightly younger than 1875 Ma.

Unlike the Gogebic and Mesabi Ranges where the stratigraphic units within the iron formation are traceable over many miles, the Negaunee is extremely variable over very short distances indicating variation in iron source, transportation, environment of deposition, diagenetic alteration and the degree of metamorphism. A general stratigraphic correlation (Figure 2) can be made by the commonality of certain features (Waggoner, 1972). For example the predominately clastic horizon present in the southeast corner of the Marquette trough and the Palmer fault block makes good marker horizon for the southeast end of the syncline.

The original mineralogy of LST and Algoma banded iron formations are quite simple in that they contain silica in the form of chert and iron in the form of carbonate, oxides, silicates and sulfides. They also contain ubiquitous apatite and can also be associated with fine to medium clastic components. Common silicates present on the eastern portion of the Marquette trough are stilpnomelane and minnesotaite. Based on the presence of greenalite on the very western part of the Biwabic range where the metamorphic effect is non existent, it can be speculated that greenalite could be a precursor to either or both these silicates. Heat or pressure can transform the low metamorphic silicates to either cummingtonite or grunerite. Further heat and/or pressure can result in these silicates becoming amphiboles and pyroxenes. Indeed, in the vicinity of the large diabase sills on the eastern end of the Range the low grade silicates have been converted to coarse grunerite. Sodium rich zones in the Negaunee contain Riebeckite (fig. 15) and Acmite (fig. 16). Sodium rich minerals are present in LST bifs worldwide. Crocidolite and riebeckite are ubiquous to the iron formation in Western Australia (fig. 17) and South Africa (fig. 18). Influx of sodium into the early sediments translates into thee minerals during diagensis or low rank metamorphism. Calcium sulfate in the form of gypsum is quite common on the eastern end of the Marquette trough and eastern end of the Palmer Fault block. It can be present in both oxidized bif or as the soft ore matrix. Its presence is detrimental to ore quality and successful beneficiation applications. Quartz veins with micaceous hematite (fig. 19) are believed to have been emplaced during the formation of the hydrothermal hard ore. Cobbles of this material are included in the basal Goodrich conglomerate.

The four major iron minerals we find today in the field do not necessarily reflect the original minerals. Banded iron formations on the Marquette Range have undergone diagenetic alteration. The majority of the magnetite (Han, 1971) and martite ore was originally carbonate silicate chert. Remnants of this lithology can be found at both the Empire and Tilden deposits. Han (1982) has shown that the core of most magnetite grains were originally very fine hematite that was altered to magnetite under a reducing diagenetic environment. The magnetite carbonate horizon at the Empire Mine was the exception as there was never any primary hematite and the magnetite formed was due to selective volume for volume replacement of iron carbonate. The seed hematite is found through the major bifs in the world (Han, 1988). The bulk of the magnetite, formed as a replacement to the iron carbonate, is fine grained (less than 50 microns) and exhibits a sooty gray black color. The carbonate is generally a mixture of siderite, ankerite, iron dolomite and calcite with variable amounts of Ca, Mg and Mn.

With an abundance of Fe^{++} available much of the iron carbonate has been converted to magnetite with or without a fine hematite precursor seed core. Most of the iron silicates we see in the iron formation are either due to conversion of preexisting silicates/carbonate during digenesis ore metamorphic processes. Sulfides are conspicuous by their general absence from both the stratigraphic column and specifically in the Negaunee iron formation. However, at some places where hard ore is found, sulfides do occur and can be locally abundant. Pyrite and chalocopyrite predominate but bornite and pyrrhotite have been noted. A suite of sulfides representing nine geographical locations was analyzed for sulfur isotope values (Waggoner, 2006). Sulfur isotope values ranged from .02 to 6.8 %o indicating they most likely were hydrothermal in origin and support the hydrothermal origin of hard ores in general.

Jasper may form by replacement of the gray/white chert with fine hematite resulting in orange jasper like that found at the Milwaukee-Davis south of Negaunee (fig. 20). This replacement method usually leaves "islands" of unaffected chert suggesting the replacement. Most of the bright red jasper on the eastern portion of the Marquette trough shows multi hued layers but they do not show any indication of replacement like cross cutting veins and gradation to gray/white chert. The bright jasper could be primary at a vent site that in turn grades laterally into normal color chert and carbonate as opposed to replacement of the chert carbonate. The presence of fine microplaty hematite as veins and diffusions (fig. 21) in the jasper shows definite signs of cross cutting and replacing the jasper. Replacement of the jasper proceeds from simple fracture and vein filling through brecciation and silica removal resulting in a high grade hard hematite ore. This sequence of replacement can be illustrated by a sequence of samples showing the stages of replacement (fig. 22-26).

There is only a little existing evidence of life forms in the Negaunee unlike the Gunflint and Biwabic where there is evidence of extensive reef building. Mancuso, et al (1971) described some physical features that could be algal mats. Lougheed, et al (1973) described hematite framboid psuedomorph after pyrite that could have formed from a decaying biomass of some life form. Han et al (1992) described floating algae (fig. 27) that were preserved in the slaty layers of the magnetite-carbonate-silicate horizon of the Negaunee mined at the Empire Mine. Evidence suggests various life forms thrived in the environment associated with the generation of banded iron formations. Many workers have suggested life forms are integral to the precipitation of the iron minerals in bifs, however, preservation of the delicate banding of the chert in all color forms suggest life was not a major presence at the time of formation. Moreover life forms are not the only ways the banded iron formations could have formed. A combination of particulate matter and hydro gels can also be hypothesized. Iron formations have rationally been viewed as an entirely chemical precipitate. Since 1977 we now know sulfides can form instantly upon exiting vents (black smokers) as can calcium and silica (white smokers). It is quite possible that iron in the form of hematite and magnetite (temperature sensitive) can form in this same manner and accumulate as discrete bands. Both hydrothermal hematite and magnetite exhibit a metallic luster unlike hematite and magnetite generated by diagenetic replacement or supergene oxidation/enrichment seen on the eastern Marquette Range.

James (1955) indicated primary hematite and magnetite are fairly inured to conversion to other forms during either diagensis or metamorphism other than expand in crystal size.

In addition to diagensis and metamorphism there is supergene oxidation and enrichment of carbonate, silicates and magnetite to hematite, goethite and martite (James, 1953). Near surface oxidation and enrichment make a good case for top down oxidation by meteoric waters, possibly warmed by the exothermic reaction of oxidation of magnetite. The presence of certain clays (Bailey, 1960) can not easily be explained without a hydrothermal input. An example is the existence of dickite and high chrome nontronite (fig. 29) which does not generally form from weathering.

The Negaunee iron formation on the northeast corner of the Marquette trough was originally iron carbonate silicate chert that has undergone supergene oxidation and enrichment to ore grade (fig.30 and 31). On the Marquette Range syncline axis form loci for ore formation floored by impervious slate or intrusives. Supergene ores generally form in structural lows where the underlying rock, in this case slate, is relatively impervious (Figure 3). In some instances basic dikes or faults can further constrain the formation of ore. On the Marquette Iron Range the bulk of supergene ore has been extracted by underground methods resulting in extensive caving of the surface due to poor structural integrity of the overlying rock.

The chemistry of the various ore types shows the iron is usually increased during diagensis (Table 3).

Table 3

MARQUETTE RANGE IRON ORE CHEMISTRY

	Carb	**Silicous**	**Hard Ore**		**Soft Ore**	
	Empire*	**Richmond**	**Cliffs Sft**	**Republic**	**Athens**	**Salisbury**
Method	OP	OP	OP/UG	UG	UG	UG
Ore Type	carb chert	hem-mart.	fine hem.	spec.	earthy hem.	
sol. Fe	30.5	39.5	61	64.3	52.9	51.5
silica	28.9	37.3	8.61	5.35	6.04	7.83
alum.	1.37	0.98	1.24	1.38	2.56	1.15
phos	0.1	0.042	0.163	0.074	0.114	0.091
lime	1.29	0.23		0.46	1.14	0.7
magnes.	4.6	0.37		0.36	0.73	0.46
Mn	0.6	0.09	0.07	0.5	0.43	0.45
H2O	0.7	3.22	1.21	0.5	12.5	12.5
s		0.018	0.029	0.01	0.011	0.016

*** Source-USGS PP 769**

Source of others American Iron Ore Association Annual Analysis Book

The Negaunee iron formation on the northeast corner of the Marquette Syncline was originally iron carbonate silicate chert that has undergone supergene oxidation and enrichment to ore grade. The syncline axis forms loci for ore formation floored by impervious slate. Supergene ores generally form in structural lows where the underlying rock, in this case slate, is relatively impervious. In some instances basic dikes or faults can further constrain the formation of ore. On the Marquette Range the bulk of supergene ore has been extracted by underground methods resulting in extensive caving of the surface due to poor structural integrity of the overlying rock.

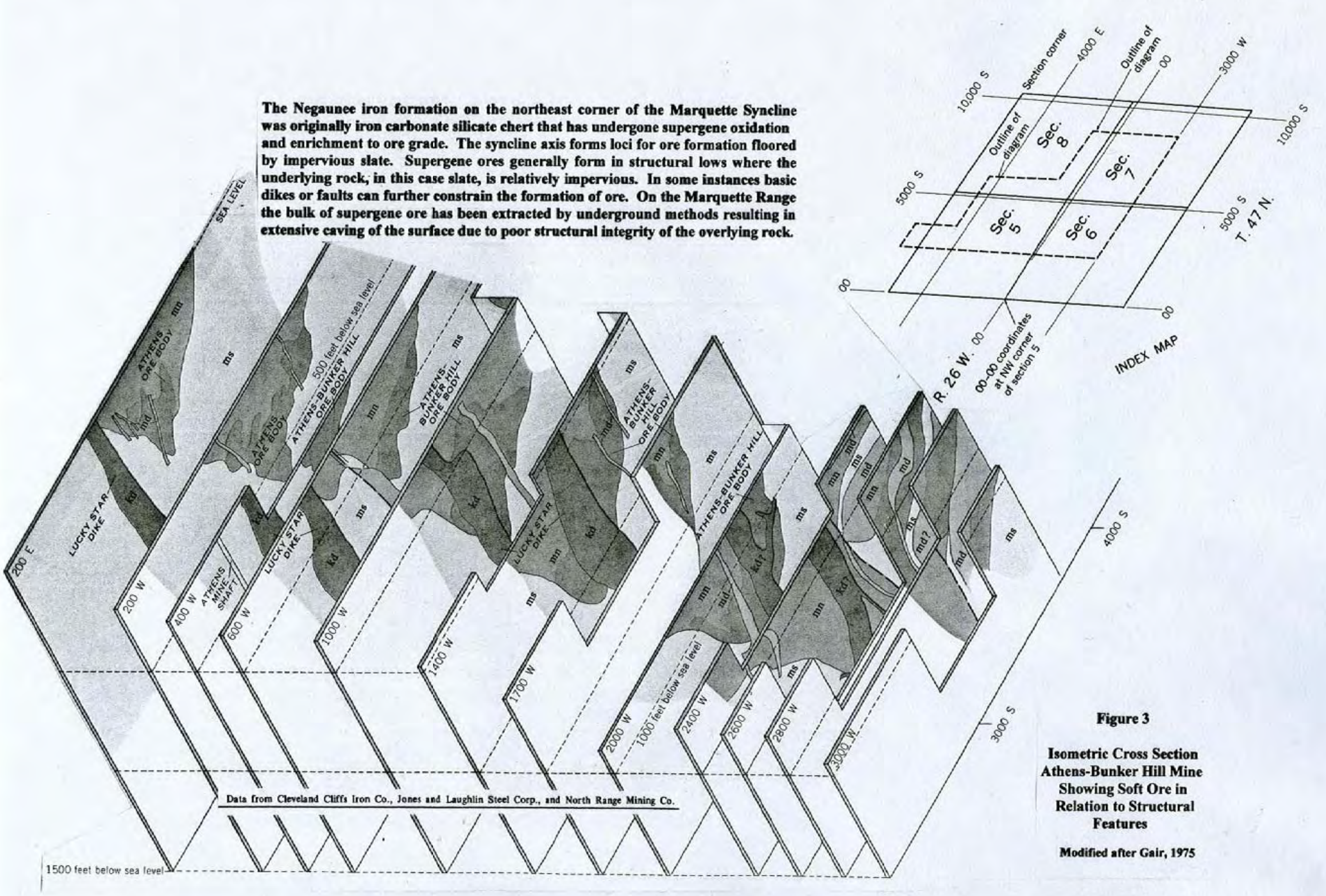

Figure 3

Isometric Cross Section Athens-Bunker Hill Mine Showing Soft Ore in Relation to Structural Features

Modified after Gair, 1975

Magnetite replacement of carbonate increases the iron while removing Ca, Mg and Mn. Oxidation of the ferrous iron to martite again increases the iron. Supergene oxidation and enrichment of the carbonate silicate chert increases the iron and reduces the other elements. Under some circumstances the manganese is also enriched as evidenced at the South Jackson and Lucy Mines in Negaunee. The uniformity in the chemistry for the Marquette Range soft ores (Table 4) suggests similar process acting on a common carbonate silicate chert protore.

Table 4

Marquette Range Soft Ore Partial Chemistry

Mine	Tracy*	Salisbury*	Maas*	Negaunee*	Athens*
Ore Type					
Method	underground	underground	underground	underground	underground
Element					
Fe	54.1	51.5	52.4	52	52.9
Silica	6.57	7.83	7.1	6.86	6.04
Al2O3	2.24	1.15	2	2.39	2.56
Phos	0.08	0.091	0.089	0.083	0.114
Lime		0.7	1.29	0.42	1.14
Mag.		0.46	0.25	0.36	0.73
Mn	0.29	0.45	0.23	0.2	0.43
H2O	9.45	12.5	11.2	12.2	12.5
Sul.	0.315	0.016	0.011	0.014	0.011

***Data Source AIOA book**
Tracy--1962, Salisbury--1916, Maas--1916
Negaunee--1916, Athens--1930.

From east to west there is a progressive change in the metamorphic mineral assemblage as indicated by James (1955). This is based primarily on the altered mineral assemblages in the iron formation. The associated stratigraphy both above and below the Negaunee do not necessarily show the same degree of alteration suggesting that much of the metamorphic effect is due to the late hydrothermal imprint of hematite and magnetite replacing earlier iron formation.

Baraga Group

Goodrich Quartzite

The basal portions of the Goodrich in a few areas contain a unique conglomerate consisting of pebble of white vein quartz, jaspilite, oolitic jasper and hard hematite fragments. In some areas the interstices of the conglomerate are filled with hydrothermally emplaced hematite. Zones which have exhibited a high iron grade have been mined as iron ore (fig. 31). The Hard Ore Mine in Ishpeming and the Republic Mine have had considerable production from such deposits.

The Goodrich Mine production came entirely from within the conglomerate. The schistose hematite pebbles where the hematite is arranged parallel to the chert banding now shows a chaotic arrangement indicating the schistose nature was present before being included in the conglomerate forming event. The presence of filled voids and replacement of fine detrital grains with hematite indicates the hydrothermal process continued throughout the period of conglomerate formation. The presence of the conglomerate would suggest that a period of tectonic change (Figure 4) preceded the formation of the conglomerate; an event that may have indicated a change from extensional basin development to one of compression, closing off the main iron mineralization and radically altering the nature of subsequent sedimentation.

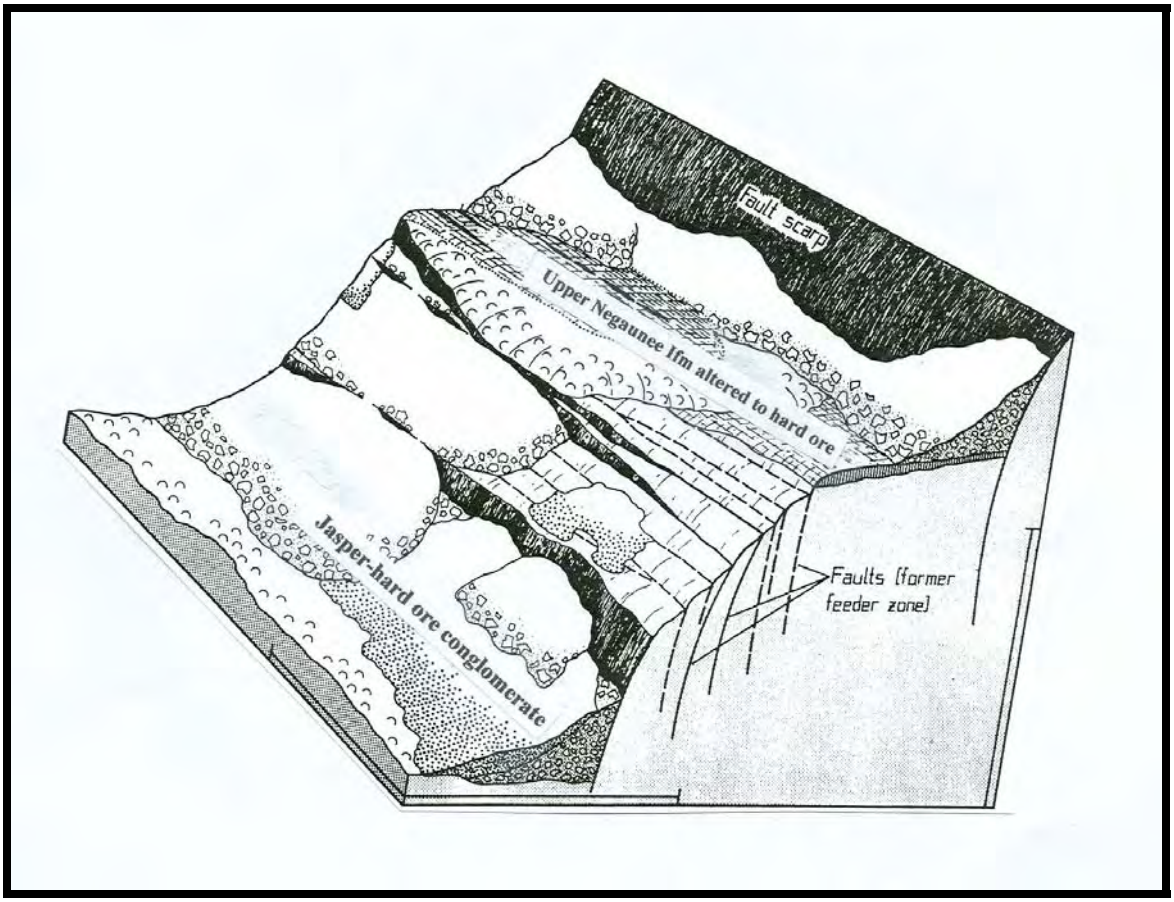

Figure 4 Possible Paleoproterozoic depositional environment for the basal Goodrich conglomerate that was facilitated by faulting. Modified after Grenne, et al, 1990

The remainder of the Goodrich is composed of a fine white quartzite with several minor argillite units. Ojakangas (1994) determined the material for the quartzite in eastern Baraga and western Marquette Counties came from the west-northwest and south east. The overall Goodrich varies from 300 to 1400 feet in thickness.

Michigamme Formation

This formation has an aggregate thickness ranging from 11,000 to 20,000 feet. Paleocurrent data recorded for the graywackes (Ojakangas, 1994) indicate the primary direction of sedimentation is from the southwest with lesser influx from the north.

Lower Slate Member

The slate unit is characterized by the presence of significant graphite (Fig. 32) and ultra-fine pyrite. The amorphous graphite as measured by the carbon content ranging from 4% to 20% as determined by Kramer (1987): Cannon et al. (1972) estimated the maximum thickness in the trough to be about 1500 feet and becoming non existent west of the Greenwood Quadrangle. In places the lower contact is phosphatic (fig. 33) and contains fluorapatite crystals as groups in a matrix or as fine phosphatic pebbles. Phosphate enrichment has been reported in nine separate areas with most sites occurring in the Dead River Basin located north of the Marquette trough. A major outcrop in the NE, section 15, T. 49 N., R. 28 W. contains a 15 meter thick areas of channel filled conglomerate. The sandy matrix contains abundant flattened and elongate pebbles of quartzite and black phosphatic slate. Drill hole and channel samples show the rock contains 15+% P_2O_5 as fluorapatite. The phosphatic pebbles weather quickly to produce negative relief on exposed surfaces. The US Bureau of Mines and Institute on Mineral Research at Michigan Technological University have been able to produce a suitable flotation weight recovery and grade on the limited resource.

Greenwood Iron Formation Member

The Greenwood was named by Swanson et al. (1930) for a laminated magnetite bearing argillite found in the lower Michigamme formation. It is present from West Ishpeming west to Humboldt. It varies from 600 feet thickness on the east end to over 1200 feet between the communities of Clarksburg and Humboldt.

The laminated or bedded rock contains hornblende, biotite/chlorite along with grunerite, magnetite and quartz. Classic iron formation chert is missing and instead higher alumna, alkalies and calcium oxide are present representing clastic (or possibly pyroclastics) input. Clastic dilution is believed responsible for the lower than normal magnetite content. Chemical data is shown in Table 6.

Table 6 Chemical Analysis Greenwood Iron Formation

SiO_2	62.34%	
Al_2O_3	6.65	
Fe_2O_3	6.22	
FeO	15.76	
MgO	2.30	
CaO	1.26	Cannon, 1972, p. 90
Na_2O	.39	N=4
K_2O	1.28	
H_2O+	1.82	
H_2O-	.07	
TiO_2	.47	
P_2O_5	.22	
MnO	.49	
CO_2	.07	
Total 99.34%		

Physical features of the magnetite suggest that it is primary (or possibly diagenetic) and not of clastic origin. The presence of the Greenwood in the same area of the Clarksburg volcanics found directly above is strong associative evidence that each emanated from the same vent area found near the community of Humboldt.

Clarksburg Volcanic Member

The Clarkburg is a member of the Michigamme Formation (James, 1958) and is composed of mafic pyroclastics, primarily tuffs (fig. 34) and agglomerated (fig. 35) with minor argillite and iron formation. It is estimated to be 2000 feet thick near the community of Clarksburg. Evidence of the center of extrusive activity around this community is present as a feeder zone that outcrops in section 18, T. 47 N., R. 28 W.

The chemical composition indicates most rocks fall in the alkaline olivine basalt range according to Cannon et al. (1972). Much of the Clarksburg displays up to 20% iron calcite replacing fragments of devitrified glass shards and plagioclase. The member does not occur on the north limb of the syncline.

Middle Graywacke/Slate Member

Bijiki Iron Formation Member

The iron formation can be characterized as a silicate sulfide chert unit with minor magnetite. It also contains the asbestos form of cummingtonite in the vicinity of the Peshekee River and US 41.

The unit varies from 100 to 200 feet in thickness. Mining from the unit has produced over 4 million long tons of iron ore, primarily limonite (fig. 36) west of Lake Michigamme.

Upper Slate Member

The Upper slate is most prevalent in Baraga County where it consists of gray to black slate, impure quartzite and greywacke. The lower segments are carbonaceous with fine pyrite. Fairly abundant concretions (fig. 37) occur within the slate. The concretions are generally rich in carbonate (Table 7) as indicated by partial chemical analysis. They are believed to have formed diagenetically by replacing both the quartz and feldspar. Henrickson (1956) has used the mineralogy of the concretions to define the relative regional metamorphic rank. The chemistry of the slate itself is shown in Table 8.

Table 7 Chemistry of Selected Upper Michigamme Concretions

Metamorphic Zone	Chlorite	Biotite	Garnet	Staurolite
Oxide Analysis*	N=2	N=1	N=1	N=1
SiO_2	29.7%	64.8	61.8	60.2
Al_2O_3	6.7	11.5	14.6	12.7
Fe_2O_3	.9	2.1	1.1	2.0
FeO	2.7	4.0	8.8	3.4
MnO	.3	-	-	.2
MgO	1.7	2.5	3.8	2.3
CaO	29.2	7.2	.7	11.6
TiO_2	.6	.6	.8	.5

*Modified after Henrickson, 1956

chlorite samples: section 2, T 46 N., R. 37 W.
biotite sample: section 19, T. 47 N., R. 32 W.
garnet sample: section 19, T. 47 N., R. 32 W.
staurolite sample: section 30, T. 48 N., R. 30 W.

Table 8 Chemistry of the Upper Michigamme Slate*

SiO_2	62.3%
Al_2O_3	15.3
Fe_2O_3	1.1
FeO	6.2
MnO	.1
MgO	3.0
CaO	.5
TiO_2	.7
P_2O_5	.1
Carbon	3.0
Sulfur	.3

Modified after Henrickson, 1956, p. 71, N=25

Near the Marquette/Baraga County line metamorphism of the Michigamme has resulted in quartz-bitotite garnet and staurolite schists (fig. 38) The Michigamme in Iron County hosts antahraxolite (fig. 39) as reported by James et al (1968) and Mancuso (1983, 1989) indicating biological activity.

Paleoprotozoic Igneous Activity

The Hemlock volcanic sequence centered on the Amasa Oval southwest of the end of the Marquette trough in Iron County is primarily basalt/andesite extrusives with lesser rhyolite extrusives. The volcanic pile exceeds 10,000 feet in thickness on the western flank of the Amasa Oval. The Fence River/Amasa iron formation found directly on top of the volcanics is equivalent with the Negaunee. The Hemlock volcanic event is believed to have provided the minerals and heat responsible for the bif. Schneider (2002) established a date of 1.87 Ga. for the rhyolite portion of the Hemlock. The Hemlock has been intruded by the large Kieranen sills which attain a thickness of 6000 feet. The Western Sill has undergone differentiation resulting in a basal peridotite grading upward into a gabbro complete with disseminated Cu+Ni sulfides to a top granophyre component complete with titaniferous magnetite. The Hemlock thins rapidly eastward and pinches out east of the Wilson Creek anticline and is not present in the south flank of the Republic Trough.

Within the Negaunee there are many sills and dikes. Numerous small sheared chlorite dikes transect the iron formation, often along faults. The chemistry of the sheared dike shows low calcium and alkalies compared to the diabase sills (Table 9) suggesting a different source for the igneous activity. Supergene oxidation of the dikes is conspicuous by the presence of earthy red hematite. Where the oxidized dikes are in proximity to the soft ores they are difficult to distinguish save for the remnant cleavage of the original rock.

The sills exhibit a diabasic texture and chemistry. Gair et al. (1970) and Simmons (1972) have described variations of gabbro, syenite and granophyres as minor and local variations. Diabase sills are resistant to erosion and form prominent ridges with iron formation occupying the erosional valleys.

The USGS has named a number of the largest sills with extended surface exposure, some as long as 7 miles and a thickness of 900 feet. The varying texture and chemistry were not part of the naming process. In the Summit Mountain sill, in section 24, T. 47 N., R. 27 W. at least three separate intrusive events were recognized by contacts, textural variations and alterations. The complexity of episodic and closely timed events has yet to be satisfactorily resolved.

All the diabasic minerals have been altered. Gair offered a (1975, p 122) description of the alteration observed.

"Plagioclase is saussuritic and albitic, particularly in the large bodies, or is variably replaced by carbonate, chert, chlorite, sericite, biotite and clay minerals; in one place, replacement is by an unusual mixture and of biotite and epidote. Original pyroxene commonly is replaced by pale-green tremolite-actinolite and minor chlorite or biotite, or entirely by chlorite-biotite."

Sill and dike contacts generally exhibit a chill margin in the diabase while within the iron formation the carbonate was quickly altered to fine magnetite that was not affected by later diagenetic crystal overgrowth noted in the rest of the iron formation. Gair (1975) noted that intrusive dikes and sills were more altered when in contact with banded iron formation than with slates or quartzites. The iron silicates, minnesotaite and stilpnomelane are elevated to grunerite/cummingtonite at many intrusive contacts. The coarse diabase was found to contain partially assimilated xenoliths of fine grained chlorite dike. Both the field relations and analytical data indicate two intrusive events with the sheared chlorite preceding the massive intrusives. Epidote which is ubiquitous to the none sheared crystalline intrusive is absent from the smaller chlorite dikes.

Within the Marquette trough the Clarksburg volcanic sequence found in the lower Michigamme strata is most likely to have provided the diabase found as dikes and sills in the underlying Archean, Chocolay group and Menominee group of the Marquette iron range. The volcanic center occurred on the south side of the trough in the vicinity of Clarksburg. A vent in section 18, T. 47 N., R. 28 W. coupled with an abundance of intrusive bodies and the thickest sequence would suggest this area was the center of greatest volcanic activity. The extrusive extends to Lake Michigamme on the west and to West Ishpeming on the east. They do not occur in the stratigraphic sequence on the north limb of the trough. Tuffs and agglomerates are common on the margins.

The chemistry of the sills generally matches (Table 9) those of the Clarksburg diabase and basalts. Amygdaloidal basalts were recognized in the Negaunee at the Greenwood Mine (Cannon, 1974) and in the northwestern portion of the Palmer quadrangle (Gair, 1975). Amygdaloidal basalt is sandwiched between a footwall slate unit in section 27, T. 47 N., R. 27 W., suggesting that there may be syn-depositional origin for at least some igneous rocks.

Table 9

Partial Chemical Analysis of Paleoprotozoic Intrusive Rocks-Marquette Range, MI

	1	2	3	4	5	6	7	8	9	10
Oxides										
SiO2	39.7			47.26	43.11	48.13		46.06	44.97	49.1
Al2O3	18.35	14.41	18.57	13.44	14.8	16.31	13.79	14.41	15.34	17
Fe	17.43	11.5	14.4	11.85	12.02	8.67	8.54	8.91	8.8	9.07
Fe2O3	16.31			7.9	1.89	1.75		1.85	1.51	2.4
FeO	16.74			8.13	13.76	9.57		9.92	9.96	9.5
CaO	0.48	0.34	0.41	0.31	1.34	8.77	7.43	8.99	7.29	10
MgO	8.33	7.74	2.68	9.35	11.62	7.47	5.53	7.16	5.91	6.9
K2O	-	0.7	-	tr	2.5	0.64	3.97	0.71	1.53	0.6
Na2O	-	0.51	0.4	0.48	2.15	2.05	4.48	2.12	4.49	2.6
TiO2	1.8	1.68	2.5	1.33	3.08	0.96	1.95	1.37	1.96	1.4
MnO	0.14				0.41	0.17		0.22	0.29	0.3
P2O5	0.26				0.41	0.17		0.22	0.29	0.3
N=	12	8	3	1	1	6	4	2	2	
					Trace Metals in ppm					
V		283	259				252			
Ni		103	90				94			
Cu		184	40				129			
Cr		60	219				223			
Co		43					57			

Sample # **References**

1 **Chlorite dikes at the Empire Mine. USGS PP 76- p. 123 Gair and Han 1975**
2 **Sheared un-oxidized chlorite dikes at the Tilden Mine, Sec 25 & 26**
3 **Sheared oxidized chlorite dikes at the Tilden Mine, Sec. 25 & 26**
4 **A 20 foot thick chlorite dike at the Tracy Mine, Sec. 8, 47-26 Mathias 1958**
5 **Clarksburg tuff, Cannon GQ-1168 p. 8 table 1 1974**
6 **Large meta-diabase sills T. 47N., R 26 & 27 W., Mathias table 3, 1958**
7 **Fine-medium unoxidized meta-diabase, Tilden Mine**
8 **Meta-diabase Clarksburg Quadrangle, Cannon USGS Map GQ-1168, table 1 p.8 1974**
9 **Metabasalt Clarksburg formation. Cannon USGS Map GQ-1168, table 1, p.8, 1974**
10 **Typical basalt**

The latest intrusive event is marked by a few scattered quartz, ankerite and micaceous veins that cut both chlorite and meta-diabase dikes but do not cut the Keweenawan dikes. The large micaceous hematite crystals show the occasional striations that resemble twinning. The quartz is milk white and the carbonate is cream white to light brown in color. None of the veins persist over significant distances.

Keweenawan Diabase Dikes (1108 Ma)

Reversely polarized Keweenawan diabase dikes are present throughout the Marquette iron range. They exhibit an east-west trend with a near vertical dip. One narrow dike has been traced over a three mile strike length and down dip over 1200 feet. The diabase ranges in width from 6 inches to 80 feet and locally bifurcates over short strike distances. Where fresh the diabase is a dark green to black and with a clear dibasic texture. Where the diabase cuts iron formation the diabasic texture is obliterated by complete alteration to clay minerals. Where the Keweenawan dikes cut older sills and dikes in the iron formation, the diabase dikes appear fresh and unaltered suggesting contact with the evolving oxidation of the iron formation facilitated the dike alteration. The altered color is generally olive green with occasional oxidation of the contact zone to a slightly yellow color. Altered dikes are quite susceptible to weathering. Newly exposed surfaces usually disintegrate within two weeks. Rapid weathering explains why the dikes have not been observed in outcrop. Where the Keweenawan dikes have been observed in underground workings they are always argillized where they cut enriched natural ore bodies.

Table 10

Selected Partial Analysis of Keweenawan Diabase Dikes, Marquette Iron Range, MI

Sample I.D.	Coordinates	Description
T25-7-732	NA	altered diabase
T26-75-1119	NA	altered diabase
EM-1165-2	18,740S, 3,450W****	altered diabase
EM-1340-1	20.570S. 2,370W	altered diabase
OV-1	NENW Sec.31 47-26	unaltered diabase

	Per Cent							
	FeO*	SiO2**	Al2O3	CaO	MgO***	MnO	K2O	Na2O
T25-7-732	9.08	57.2	16.24	1.55	3	0.01	0.24	0.84
T26-75-1119	21.09	42.26	14.26	2.6	7.5	0.02	0.6	1.46
EM-1165-2	25.46	28.88	16.36	0.62	7.8	0.06	0.1	1.11
EM-1340-1	16.08	23.06	20.14	1.07	6.3	0.01	1.01	1
OV-1	14.66	60.1	13.58	8.64	3.3	0.02	0.06	2.88

	ppm							
	P2O5	TiO2	V	Ba	Ni	Cu	Cr	Co
T25-7-732	0.042	0.57	575	967	49	153	122	37
T26-75-1119	0.029	0.85	499	1660	55	430	65	60
EM-1165-2	0.024	0.3	281	1950	19	64	29	50
Em-1340-1	0.048	0.57	641	1180	48	316	115	50
OV1	0.014	0.24	409	1250	60	324	70	70

Sample Legend

T = Tilden Mine DDH-Sec.-hole#-footage in hole
Em = Empire Mine bench sample-footage
OV-1 = Isabella dike in sec. 31, T. 47 N., R.26 W.

*** Soluble iron calculated as FeO**
**** Titration analysis**
***** Wet Chem.**
****** Mine triangulation coordinates**
******* 1978 Barringer 42 element analysis-Co@, H2O and S not determined**

Although they do not control enriched ore concentrations like the older intrusives, they were definitely altered by the solutions acting in the porous oxidized and enriched zones.

Gair (1975) suggested the solutions responsible for oxidation of the iron formation were active after Keweenawan time and were a causative effect in the alteration of the Keweenawan dikes. Table 10 shows the chemical variation found within the altered dikes. Alteration of the Keweenawan dikes resulted in a pronounced reduction of silica and calcium where the dike was in contact with ferrous iron formations (i.e. Empire) and to a lesser extent in a ferric environment (i.e. Tilden)

Recent dating of the Eagle nickel-copper deposit indicates that it is 1107+-3.7 Ma. and establishes a good age for the general Keweenawan diabase event. Paleomagnetic data and chemistry of the abundant east-west Keweenawan dikes are similar to the Logan sills of the North Shore Volcanic group that have an age of 1108 matching the recent Eagle number. Northwest faults offset the Keweenawan dikes and indicate that the age of the offset is younger than 1108 Ma. The dikes are devoid of any metamorphic fabric.

Structure

Schulz (2007) summarized the Penokean Orogeny as starting with the collision of oceanic, island-arc terrain (the Pembine-Wausau terrain of Wisconsin) with the Archean Superior craton to the north. Upon collision the direction of subduction flipped to the north, creating extensive back-arc extension. This resulted in the development of the Animikie basin into which a thick group of sedimentary and volcanic rocks representing the Menominee Group were deposited. The accumulation included the Negaunee iron formation and its equivalents in other iron districts. The north-directed subduction brought the Marshfield terrain toward the Superior craton. The Pembine/Wausau island arc was thrust north onto the Superior craton resulting in subsidence of a foreland basin into which the Baraga group of sedimentary rocks, including turbidities, and volcanics were deposited. This took place between 1850 and 1835 Ma. Metamorphism occurred during folding, thrusting and tectonic thickening resulting in a metamorphic gradation of existing rocks accumulated during the Penokean Orogeny. The end of the Penokean was marked by emplacement of a number of plutons in the metamorphosed terrene.

A north-verging fold-thrust system in the early Paleoproterozoic continental foreland in northern Michigan has been recognized by many workers (Cannon, 1973 and Klasner, 1978, 1991). Initial deformation caused thin skinned shortening of the Paleoproterozoic strata along decollements. This deformation also formed north-verging structures along with south-dipping foliation. Subsequent deformation involved block uplift of the Archean basement and formation of structures such as the Marquette and Republic troughs and possible development of Archean gneiss domes.

One other structural event was active from early Chocolay sedimentation up through the end of Menominee sedimentation. A significant down warping occurred in the vicinity of section 6, T.

47 N., R. 25 W. for the Chocolay sequence (Taylor, 1972) and migrated to the southwest to roughly the current position of sec. 19 T. 47 N., R. 26 W. where the Negaunee iron formation attains a thickness of over 1000 meters. The Wewe slate and Siamo slate, including the Goose Lake iron formation occur only in the eastern portion of the trough in the same down warping progression event. It is possible that a detailed study of the stratigraphy of either or both the Wewe and Siamo would reveal a similar thickening along the same NE-SW trend line.

The north and south margins of the Marquette trough are bounded generally by high angle faults. The east-west Palmer fault, forming the south boundary of the Tilden ore body, dips uniformly at 55 degrees to the north.

FIELD TRIP STOPS 1 THROUGH 8

IRON ORE HISTORY

Although iron ore was discovered in outcrop in the vicinity of Negaunee in 1844, production was slow to materialize due to the poor to non existent transportation system. Early ore production went to a number of local charcoal furnaces that produced pig iron using charcoal produced from the local forests. As railroads were built and a system of boat locks installed at Sault Ste Marie in 1855 to accommodate large lake vessels, production of raw iron ore increased and moved to the lower lake steel mills.

Initial iron ore mining concentrated on open pit hard ores that formed topographic highs. Discovery of soft enriched supergene ore on the eastern end of the range followed along with the application of underground extraction starting in 1880. These two types of ore were augmented by siliceous ore which was slightly enriched banded iron formation used for furnace slagging. By the 1950's high grade ore reserves were almost depleted on most of the iron ranges in North America. This spurred the advent of beneficiating techniques to upgrade the banded iron formation into a high grade concentrate that could be pelletized for superior furnace operation. On the Marquette Range the first concentrating/pellet operation was the Humboldt Mine opened in 1954 followed by the Republic Mine opened in 1956. Both used an anionic hot oil flotation system to concentrate the specular hematite. The Empire Mine was opened in 1964 and used magnetite separation. The Tilden Mine followed in 1974 using a cationic silica flotation to concentrate the hematite. It should be mentioned that the soft ores from the Mather A underground mine were pelletized up until the mine closed in 1978.

Thomas A. Edison invested the proceeds from the sale of his electric business to GE into iron mining and beneficiating schemes to upgrade magnetite banded iron formation to produce a salable concentrate product. In 1888 Edison provided the financial backing to Walter Mallory to construct a crushing/grinding/electro magnetic separation operation at Humboldt utilizing ore from the Sampson Mine (later to be included as part of the Humboldt Mine in 1952). The Edison Iron concentrating company began operation in 1889 and produced 893 long tons of magnetite concentrate up until a fire destroyed the mill in 1890. The mill was not rebuilt and Edison turned his attention to Fe-oxide deposits such as the magnetite in gneiss at Ogdensburg, New Jersey. He essentially went broke on his mining and concentrating activities partly because concentrate (small size) was not the preferred furnace feed. He was an inventor and his electro magnetic separation and roll crushing are integral to North American iron ore operations today.

The last operating underground hard ore mines were the Cliffs Shaft and Champion Mine and they ceased operation in 1967 and 1968 respectively. The last underground soft ore mine on the range was the Mather B which ceased operation in 1972. The last siliceous mine was the Old Tilden Mine that shipped its last loads in 1973. The Humboldt ceased production in 1974 due to exhaustion of the ore while the Republic Mine shut down in 1981 due to difficult economic circumstances.

Each field trip stop is identified by a latitude, longitude and elevation that can be used with a GPS to locate the outcrop on the ground.

Stop 1 - Wewe Hills Vents

section 21-23, 47-26

A- 46^o 27' 13.22" N, 87^o 32' 38.96" W, +1503
B- 46^o 27' 16.07" N, 87^o 32' 47.17" W, +1505
C- 46^o 27' 41.99" N, 87^o 33' 8.23" W, +1514

Stops 1 A-C are located on a continuous silicified/hematite zone adjacent to a fault, both of which trend N 30^o W and is at least 6000 feet long. The stop exhibits similar features found in a number of other localities on the eastern portion of the Marquette Range. Most occurrences contain quartz and hematite stockworks that were emplaced by episodic pulses of silica usually followed by the emplacement of hematite/jasper. The hematite habit varies from botryoidal to microplaty through specularite to very coarse micaceous hematite.

Rare earth analysis of the hematite shows high concentrations of LREE relative to HREE (Waggoner, 2003). The REE pattern of the vent hematite is mirrored by the hard ore hematite mined from the upper portion of the Negaunee Iron formation.

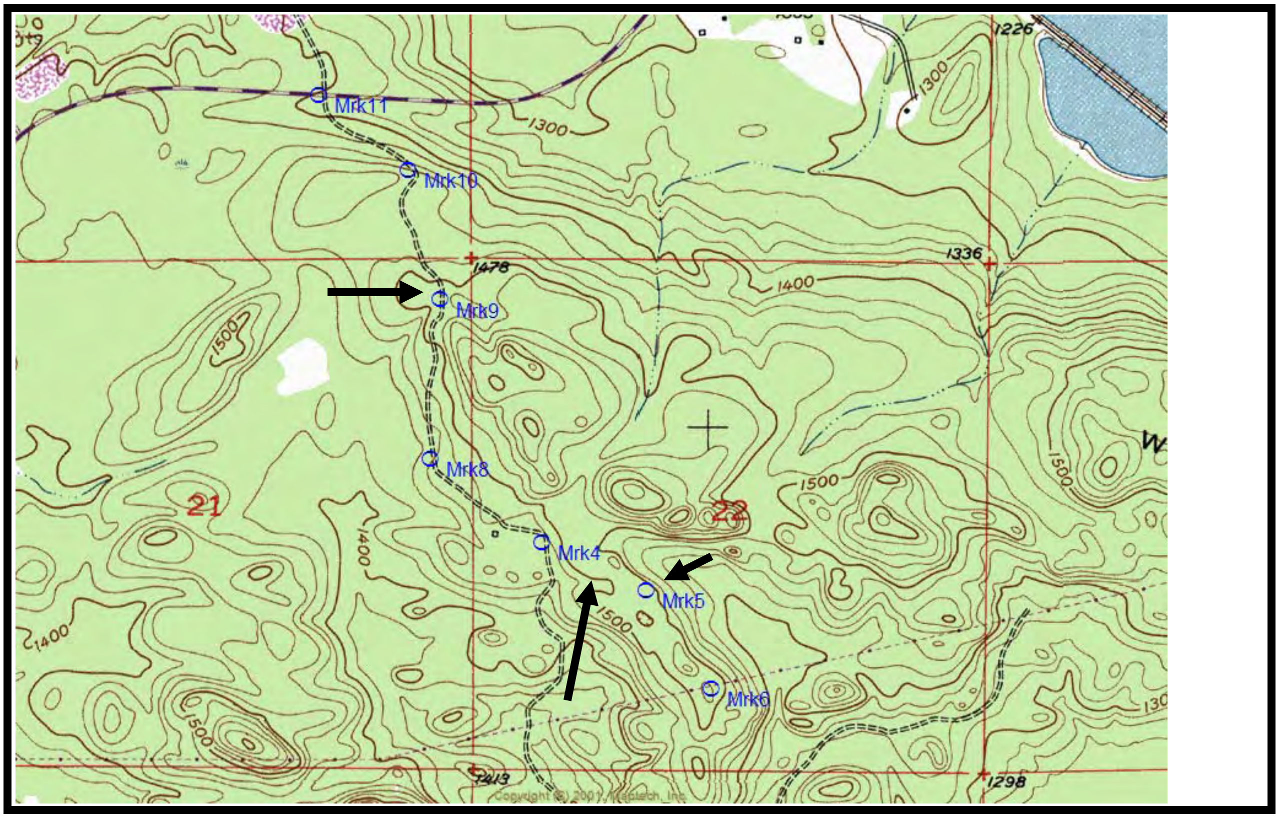

Figure 1-1 Wewe Hills Stockworks. Stops A, B and C

There has been considerable discussion in regard to the proper placement of these rocks within the stratigraphic section. Van Hise (1897), Van Hise & Leith (1911) and Gair (1975) thought the major slate lithology represented the Wewe slate. Taylor (1972) was able to identify the silicified rock in sections 23 & 24 as the big cusp algal dolomite member of the Kona formation making it more likely that the rocks directly above the basal conglomerate in sections 21 & 22 also belong to the Kona formation. Further east in section 23, directly above the silicified Kona, much of the slate has been hydrothermally altered. Gair (1975) has described chloritoid, andalusite (fig. 40), pyrophyllite and cordierite associated with sericite, chlorite and quartz alteration.

In the venting process the elements of iron, silica, potassium, sodium, calcium manganese and aluminum are vented in solution or as fine particulates into a sea water environment. Settling and precipitation resulted in the formation of a banded sequence rich in one or more of the elements as carbonates, oxides or silicates. These same elements when confined to an intrusive or replacement environment resulted in zoned alteration of the host rock. The configuration of the venting in the Wewe Hills suggests the plumbing was linear that allowed for variable volume of discharge along its entire length. On the Marquette Range circumstantial evidence suggests the zone of weakness was present on or near the south side of the trough.
Certainly the presence of the Clarksburg and several other Michigamme units only on the south side of the trough points to a weak zone in this location through which the fluids vented.

During the venting process elements of iron, silica, potassium, sodium, calcium, manganese and aluminum are vented in solution or as particulates into a seawater environment. Differential settling and precipitation resulted in the formation of a banded sequence rich in one or more of the elements. These same elements when confined to an intrusive or replacement environment in rock result in zoned alteration. The configuration of the stockwork zone in the Wewe Hills suggests the plumbing was linear and allowed for variable volumes of discharge along the entire length. On the Marquette Range circumstantial evidence suggests the zone of weakness was present on or near the south edge of the trough. Clear timber cutting has aided visual inspection of silicified dolomite/slate units similar to those found to the east of Goose Lake

Stop 1A. This outcrop consists of silicified slate and dolomite belonging to the undifferentiated Chocolay Group. The stockworks quartz (fig. 41) trends similar to that of the outcrop. Cross cutting hematite veins (fig. 42) with disseminated wall rock alteration can be distinguished by the red color. The dolomite contains breccia units where the silicified dolomite contains fine specular infill that in some areas resemble a crackly breccia. The breccia contains coarse quartz veins with minor micaceous hematite.

Looking east across the valley the large outcrop is an orange to green boulder conglomerate (fig. 43) forming the basal Chocolay Group. Some parts of the conglomerate in sections 21 & 22 contain specularite and martite (fig. 44) replacing the fine fractions of the matrix in the conglomerate usually near shears and joints that acted as a fluid conduit.

Stop 1B. The early exploration for iron ore resulted in the excavation of the shallow test pits where high concentrations of iron were encountered . The three to four foot near vertical vein of hematite jasper breccia was tested for size and grade at this location. The episodic injection/dilation caused openings to form into which fine hematite was precipitated as botryoidal hematite (fig. 45). This will be one of two places for Stop 1 where samples can be collected.

Stop 1C. This is another early exploration where shallow excavation was used to examine both grade and size of the hematite concentration. The outcrop next to the road is an excellent example of the quartz stockworks overprinted by microplaty hematite and jasper veins. The red oxidation present in the gray green slate is defiantly later than the foliation and as such may be a later event not related to the quartz/hematite which occurred before the end of Goodrich time. This feature is mentioned because this kind of oxide staining at the Wernecke deposit in the NW Territories is believed to have occurred with the metallic oxide alteration.

First day lunch stop will be at the Iron Industry Museum

For any of the following Tilden and Empire ore types we are unable to access due to ongoing operations, core and samples will be on display at this lunch break.

Core:
- magnetite silicate iron formation-Empire Mine
- magnetite carbonate iron formation-Empire Mine
- carbonate chert iron formation-Empire Mine
- clastic magnetite silicate chert-Empire Mine
- ultrafine magnetite at diabase contact

- soft hematite ore-Cascade Range
- “blue steel” ore-Cascade Range
- supergene enrichment-Cascade Range
- earthy hematite (like Mather ores)- Cascade Range

- goethite chert-Tilden Mine
- leopard goethite-Tilden Mine
- martite clastics-Tilden Mine
- magnetite carbonate chert-Tilden Mine
- martite hematitic chert-Tilden Mine
- martite chert-Tilden Mine

Stop 2 - Tilden & Empire Mines

section 18, 19, 20, T. 47 N., R. 26 W. and sections 22-27, T. 47 N., R. 27 W.

The advanced development of these mines can afford many excellent features of the Negaunee Iron formation on the eastern end of the Range. The Negaunee is over 3000 feet thick in section 19. It has been divided into a lower transition unit that contains fine clastic material, a magnetite silicate horizon (fig. 46), a magnetite carbonate horizon (fig. 47), a clastic horizon (fig. 48) and finally an upper undifferentiated unit. All horizons have provided some ore but the largest sources are the magnetite silicate and magnetite carbonate horizons located in the center of the pit (see Table 2). The protore on the eastern end of the range was a fine iron carbonate silicate chert (fig. 49). Remnants of this type of material occur on the hanging wall of the Empire pit and the SW extension of the Empire pit, the deep portions of the Tilden pit and the Tilden CD III extension adjacent to the Keweenawan dike. Both mines exhibit good exposures of the clastic component of the iron formation. Good examples of the martite after magnetite are found in the Tilden ore horizon.

Stop 3 - Marquette County Rd. 480

46*29"89.49"N 87^{o} 35' 51, 17"W +1391

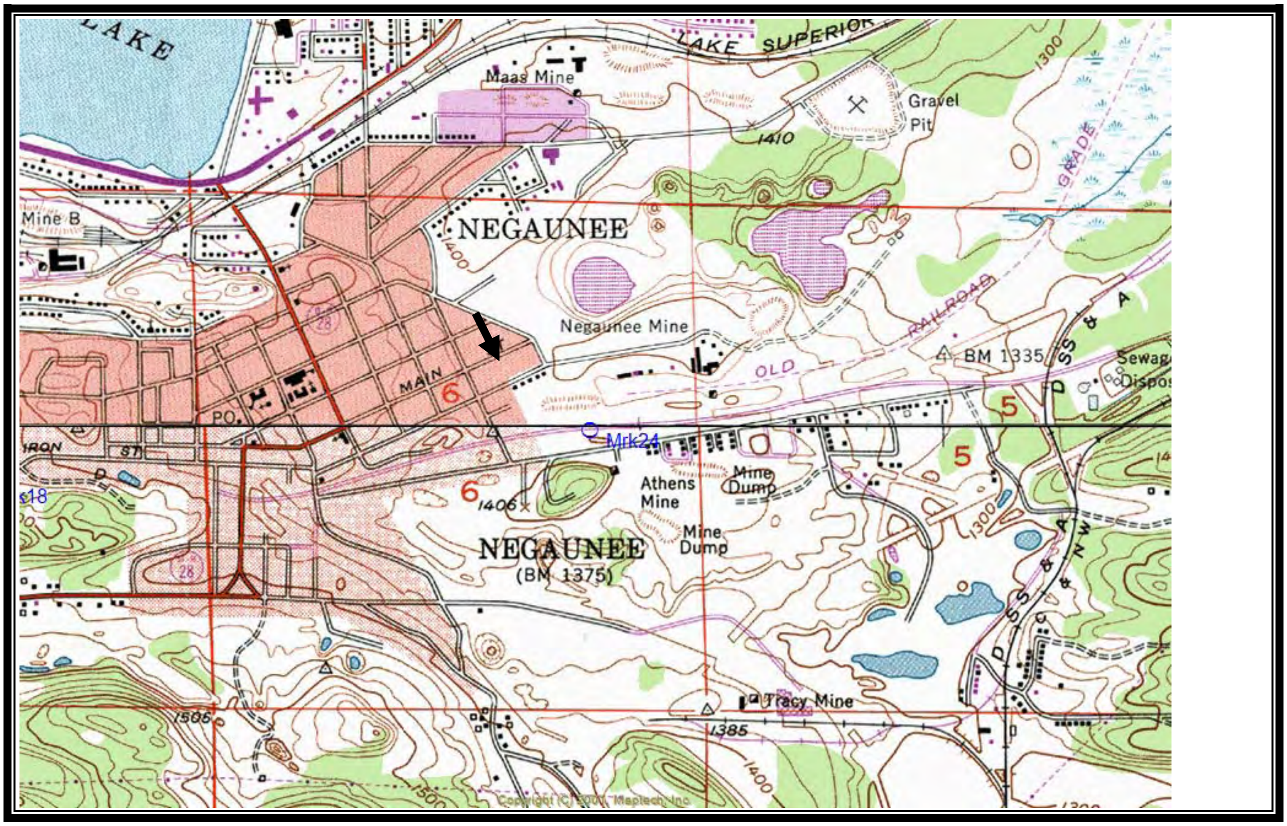

Figure 3-1 County Road 480 road cut

This stop illustrates the original protore to be found on the eastern end of the Marquette trough. The outcrop in the road cut is a gray to buff iron carbonate with minor silicates and some magnetite alternating with chert. Surface oxidation is very thin and tends to develop along exposed surfaces and bedding planes. This type of iron formation is very susceptible to supergene oxidation and enrichment.

Stop 4 - North Jackson Mine

46^{o} 29' 53.98" N, 87^{o} 37' 20.48W +1428

The Jackson Iron Mine was opened in 1848. It provided iron ore for local pig iron furnaces and was the source of ore that fed the furnaces at Fayette down on the shore of Lake Michigan on the Stonington Peninsula. The site has been off limits for fifty year due to the underground Mather B operations which recovered the soft ore along the footwall of the Negaunee iron formation.

The City of Negaunee purchased the lands recently and has opened part of it for a heritage park. This action allows our group to visit a classic mining site and examine the detail geology. We will enter the very eastern portion of the old North Jackson mine where both hard hematite and soft ore were mined during the middle of the 1800s.

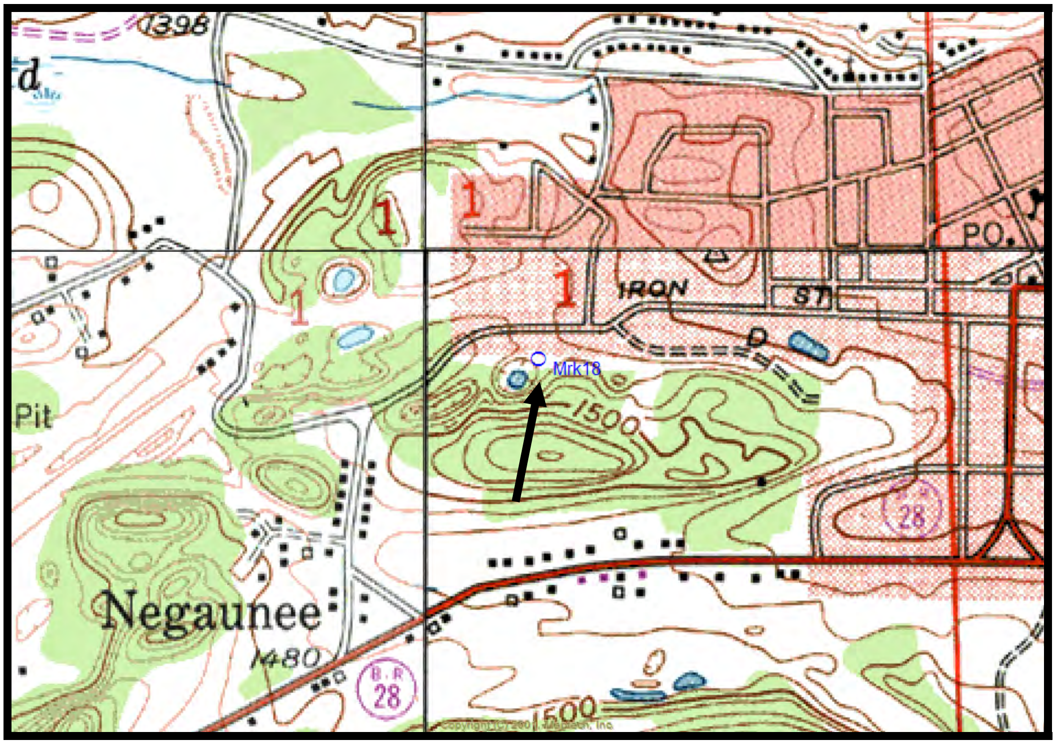

Figure 4-1 North Jackson Mine

The access cut passes through soft ore on the south wall while the north wall is formed by a vertical sheared chlorite dike possibly of Clarksburg age. The cut opens into a two level pit where the lower level is under water. On the southeast part of the pit is a rubble pile of very large blocks of jaspilite that illustrates hematite replacing jasper. The majority of the blocks appear to be breccia with cross cutting veins of hematite and occasional magnetite. One large boulder has been cleared of organic material and should afford a good photographic opportunity. On the west wall is an exploration adit (screen covered) and the south pillar shows a vuggy metallic hematite with clay filling (probably kaolin). This showing illustrates that the 1.8 million year old hard hematite was further leached by the supergene process with resulting dissolution of the remaining jasper and formation of the classic porous soft ore texture.

<u>Stop 5</u> - Jasper Knob, Ishpeming

46° 29’ 12.43” N, 87° 39’ 15.01” W +1607’

The outcrop represents the very upper portion of the Negaunee iron formation that has undergone the initial stages of hydrothermal replacement of the jasper by microplaty hematite. The laminated jasper shows only minor disturbance including brecciation. Most of the brecciation is intraformational bedding breccias (or conglomerates). The jasper bands contain less than 0.5% iron oxide.

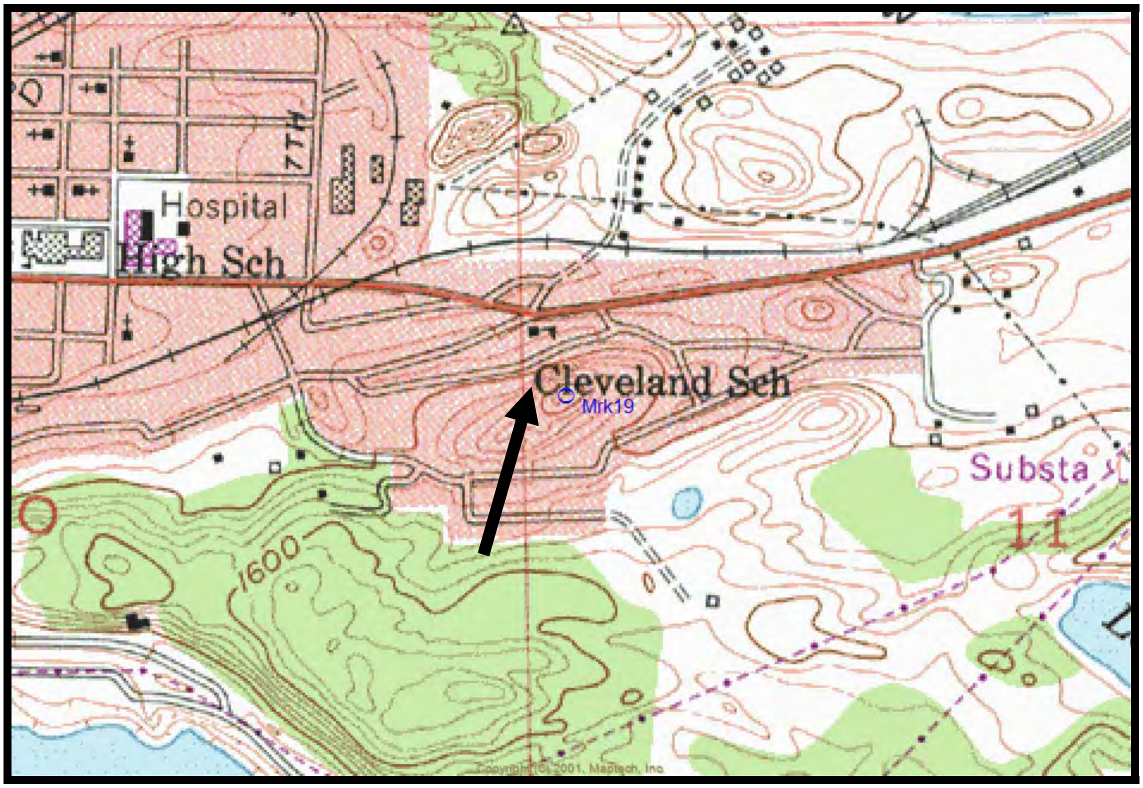

Figure 5-1 Jasper Knob

Some workers suggested oxidation and replacement of the siderite chert by jasper which in turn was replaced by hematite while others suggest a primary origin for the jasper and some of the banded hematite. Replacement of pre-existing chert/oxides by jasper (fig. 50) at both Tilden and Empire have left evidence of the process. Within the fine jasper in Ishpeming relic transitions are not in evidence. Note the undisturbed fine bedding in the jasper similar to both white and gray chert. If there was abundant fauna present, it would have disturbed the delicate banding or at least have left some evidence of its physical activity.

To complicate matters supergene oxidation can produce a brick orange chert like that present at the Milwaukee-Davis Mine in Negaunee. The process usually leaves “islands” of uncolored chert (fig. 50a) Fold axis are horizontal to gently plunging to the west. Look carefully for isolated granular or oolitic zones.

Stop 6 - Saginaw Mine

46° 27’ 26.48” N, 87° 43’ 43.36” W, +1648’

The Saginaw Mine is an interesting property due to the diverse types of banded iron formation to be found there. This is a transition area within the Negaunee iron formation on the Marquette range. To the east most of the iron formation was originally carbonate replaced by magnetite or oxidized to hematite and enriched.

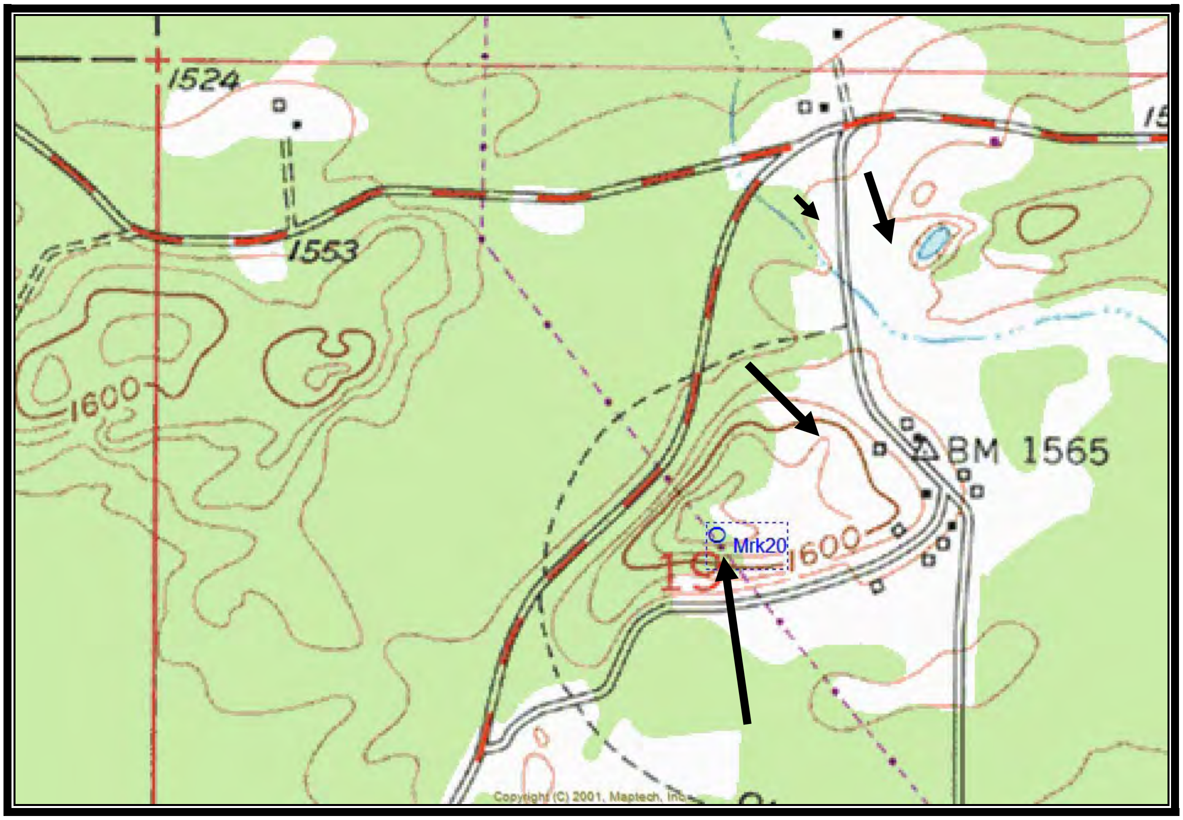

Figure 6-1. Saginaw Mine

To the west the Negaunee is primarily banded specularite chert or banded magnetite silicate chert. To the east of the Saginaw the hard ore hematite is microplaty hematite. The lean magnetite silicate chert on the Saginaw property is very coarse and contrasts with the much finer martite goethite chert up section to the north underlying the jasper-hard ore deposit that was mined from 1872 to 1891 and produced 451,000 long tons.

At the Saginaw the Negaunee begins a significant reduction in thickness to the west that may be either a function deposition or due to faulting (Simmons, 1972). Midway up the Negaunee section is a lean coarse magnetite cummingtonite chert iron formation overlain by earthy hematite-goethite chert iron formation (fig. 51) as a result of supergene oxidation of an original carbonate silicate chert iron formation. The grain size is much finer than the underlying magnetite horizon. Overlying the hematite-goethite are intermittent zones of jasper, microplaty and specular hematite. The high grade hard ore both at the top of the Negaunee and in the basal Goodrich was the target of mining at the Saginaw. Above the contact of the Negaunee with the Goodrich is a thick sequence of conglomerate consisting of jasper, microplaty hematite and minor vein quartz. The schistose nature of the hematite in the jaspilite pebbles and cobbles is parallel to bedding and occurs in random orientation in the conglomerate indicating the schistosity was present prior to incorporation of the pebble and cobbles in the conglomerate. The magnetite cummingtonite chert is fairly lean. Both the ground residual gravity and the total field magnetics indicate this unit forms a north facing thickening that could either be a fold or vent mound where coarse magnetite and iron silicates quickly accumulated in a pile. At the Little Commonwealth deposit in Florence Co., WI a small bif separates an up-slope quartzite from a down-slope slate indicating the iron formation acted as a barrier to sedimentation. This suggests positive relief to its surroundings. The Commonwealth also contains irregular shapes of silica globs that look like fiamme features. These features, however, are not present at the Saginaw.

Looking northwest along the power line clearing an outcrop can be seen about half a mile to the northwest where the power line turns north. This is one of the best outcrops (fig. 52) of Goodrich conglomerate on the range. It contains cobble of microplaty hematite, banded jasper, oolitic jasper and white vein quartz. From this vantage point there is a large boulder of the Goodrich conglomerate that illustrates many of the features of the conglomerate portion of the Goodrich. Several hundred of feet into the woods line west of the turn in the power line is the Goodrich Mine where 50,000 long tons of enriched Goodrich conglomerate (fig. 53) was mined for iron from 1873-1882. The contact between the earthy hematite chert and the Goodrich conglomerate can be seen in the adit separated by a fault breccia (fig. 54). The basal Goodrich is an unconformity by definition but the same hydrothermal event responsible for hard ore formation was active after the conglomerate accumulated as evidenced by the hematite present in the interstices between pebble and cobbles. The movement that resulted in the accumulation of coarse clasts did no stop the hydrothermal process. The microplaty/specularite conglomerate juxtaposition to the earthy hematite suggests the specularite is primary and not a metamorphic product of preexisting earthy hematite.

Although not apparent in outcrop the property contains a swarm of basic dikes and sills as determined from diamond drilling. Based on dump material at least one oxidized Keweenawan dike transects the property. From the rusty zones in outcrop very minor sulfides are present in the magnetite cummingtonite chert iron formation.

Second day lunch stop at Cliffs Shaft Mine

The Cliffs Shaft Mine Operated from 1848 to 1967 shipping 29 million long tons of high grade microplaty hematite with minor magnetite and siderite. The mine was accessed by a vertical shaft (Koepe hoist) to the 15th level-1250 feet below surface. The two cement obelisk shaped shafts were constructed in 1919. Ore was mined by room and pillar methods (see old photos on the CD). Copper sulfide veins are common throughout the ore body (fig. 55). The drainage ditch leading to the sump on the 10th level was lined by a thick layer of black copper oxide that assayed over 3% Cu. Samples of the hard ore can be found on the surface of the stocking area just west of Euclid St. (west of the shaft area).

During lunch the field trip attendees will be able to view the Hawes mineral collection and examine examples of the following:

Core
- Goodrich conglomerate – Saginaw area
- Soft supergene hematite-goethite – Saginaw area
- Goodrich quartzite contact with hard spec. ore – Humboldt Mine

Samples
- Goodrich conglomerate ore-Republic Mine
- Goodrich conglomerate polished slab – Goodrich Mine
- Coarse magnetite – Champion Mine
- Coarse specularite – Champion Mine
- Greisen with molybdenite - Champion Mine
- Sulfides associated with hard ore – various sources
- Copper sulfide – Cliffs Shaft

<u>Stop 7</u> - Kloman Exploration, Republic Mine

46^{o} 24’ 23.46”N 87^{o} 59’ 10.94”W +1517

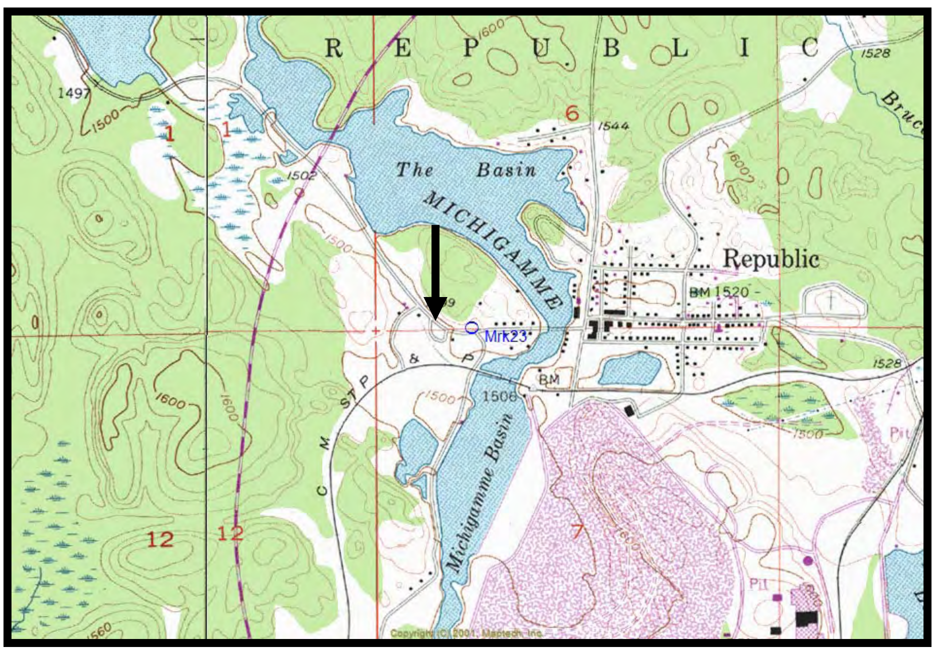

Figure 7-1 Kloman/Republic Mine

The following production history for the Republic area was tabulated:

- Republic underground 1872-1926, 8.6 MLT (60-65% Fe)
- Republic open pit 1956-1981, 62 MLT from 145 MLT of specular hematite
- Kloman/Columbia underground 1873-1883, 95,000 LT

The Republic ore outcropped in a bluff on a bend in the Michigamme River that corresponds to the mapped geology (Cannon, 1975). Initially mined from shallow pits, most production came from a number of shafts including the Pascoe (see old photo gallery on the CD) which was inclined 48 degrees down four thousand feet of the fold axis that bottomed 2900 vertical feet below the river. After being idle for many years the deposit was reactivated as an open pit to produce crude suitable for concentration. The crude feed had the following chemistry:

Sol. Fe	38%	CaO	.53%
Silica	42.5%	Na2O	.03%
Al2O3	.72%	K2O	.04%
MgO	.9%	P	.033%

The ore mined at the Republic Mine for taconite feed (1954-1981) originated from a specular jaspilite (fig. 56) found above the metadiabase sills and below the Goodrich quartzite on the southeastern end of the trough. The basal Goodrich is a conglomerate rich in specular fragments that were rich enough to constitute ore. The specularite generally contains less the 0.2% TiO2 but in the conglomerate area values of 0.50 to 1.65% TiO2 as rutile associated with hematite.

The high grade specular hematite and magnetite occur at the top of the Negaunee as irregular replacement bodies. The magnetite may indeed be post tectonic as suggested by Cannon (1973). The banded iron formation consisting of specular hematite with minor magnetite does not show cross cutting veins or disturbances to the bedding, suggesting the specular chert is a primary facies generated when the hydrothermal hematite crystallized upon release into an aqueous environment and quickly settled as distinct bands. As seen in the Saginaw Mine area the presence of coarse specularite is not a metamorphic product of a preexisting oxide form because it coexists with soft oxide hematite and goethite. Examination of the magnetite silicate horizon of the lower Negaunee iron formation exhibits a uniform banding (fig. 57), unlike the Champion area where the magnetite silicate chert has undergone hydrothermal alteration as indicated by brecciation and clear evidence of solution replacement features corresponding to the change in mineralogy. Conceptually the magnetite silicate could have resulted from the same diagenetic replacement of the original carbonate silicate chert and subsequent metamorphism resulting in conversion of the low grade silicates to cummingtonite and grunerite with enhanced size to the magnetite. It could also be primary mineralogy enhanced by metamorphic overgrowth.

The stratigraphy in the Republic trough consists of the undifferentiated Siamo and Ajibik formations, Negaunee iron formation, Goodrich conglomerate/quartzite and Michigamme slate (schist). A number of diabase sills parallel to the iron formation bedding have undergone the same folding flexure in creating the keel of the trough. The tight compressional folding that thickened the iron formation in the keel of the trough did not markedly impact the vertical and thinner iron formation on the north side of the fold. The keel plunges 48 degrees to the northwest. An excellent exposure of the upper portion of the Negaunee Iron formation can be found just north of the old pit on the Kloman property. Cannon (1972) provide a good stratigraphic section for this outcrop (Figure 7-2). The high grade lens was mined just at the Goodrich contact (fenced area). The iron formation consists of alternating bands of specularite and magnetite grading down section to more magnetite silicate chert. Compare the stratigraphy of Figure 2 with the stratigraphy shown for the Republic Mine and note the change in mineralogy over a relatively short distance.

The Republic trough area was flown for gravity using Falcon method several years ago and a drilling program was conducted on a gravity target located several hundred feet east of Highway 95 and south of the Michigamme River. An economic target was not located. Klasner et al. (1974) using gravity indicted the depth of the Republic trough on Highway 95 to be 1,424 meters.

A resource of 120 million long tons of oxide iron remains within the pit outline.

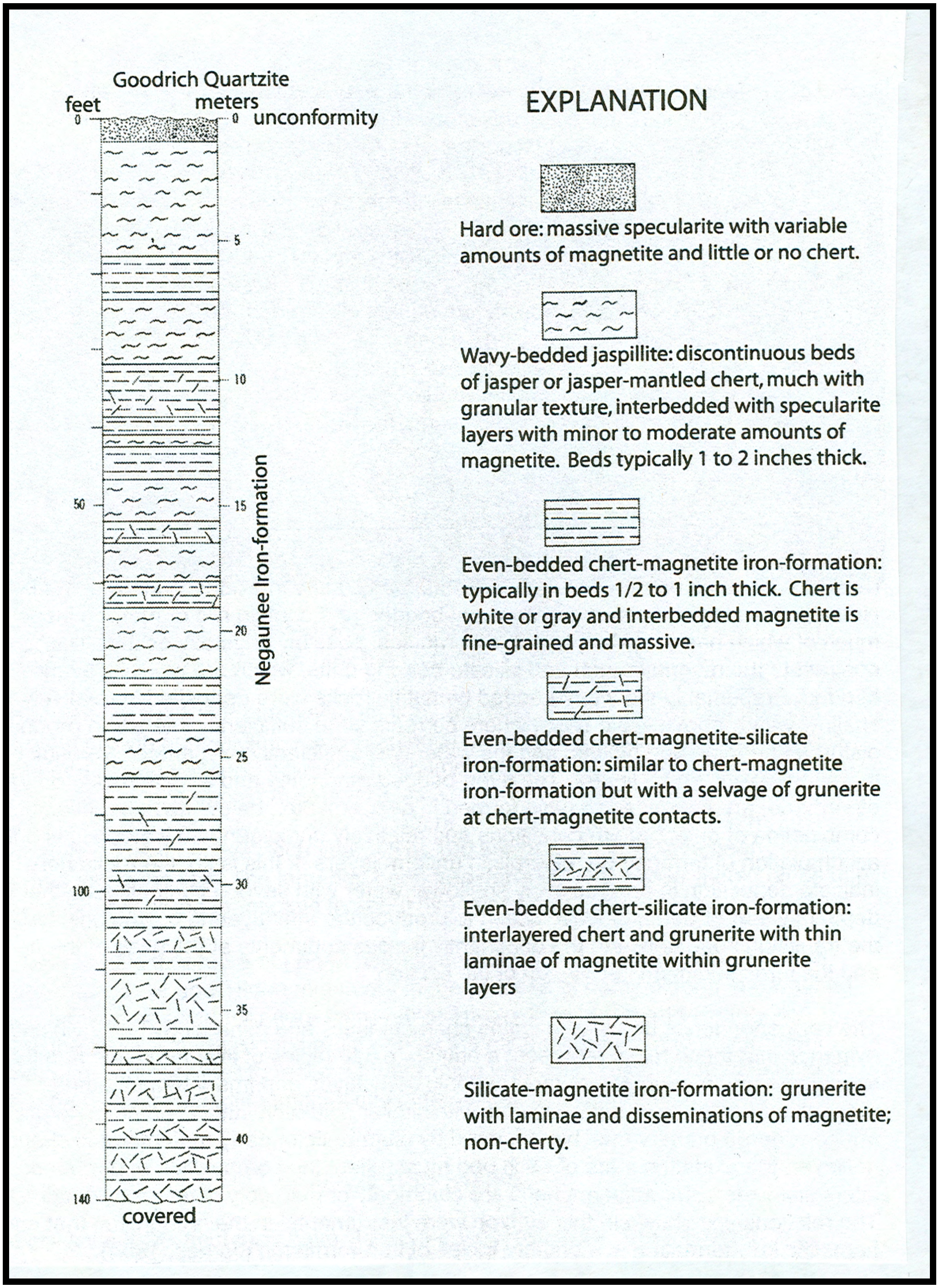

Figure 7-2 Stratigraphic section-Kloman Mine. After Cannon (1972)

Stop 8 - Champion Mine #7

46° 30’ 27.59”N, 87° 59’ 11.51”W, +1705’

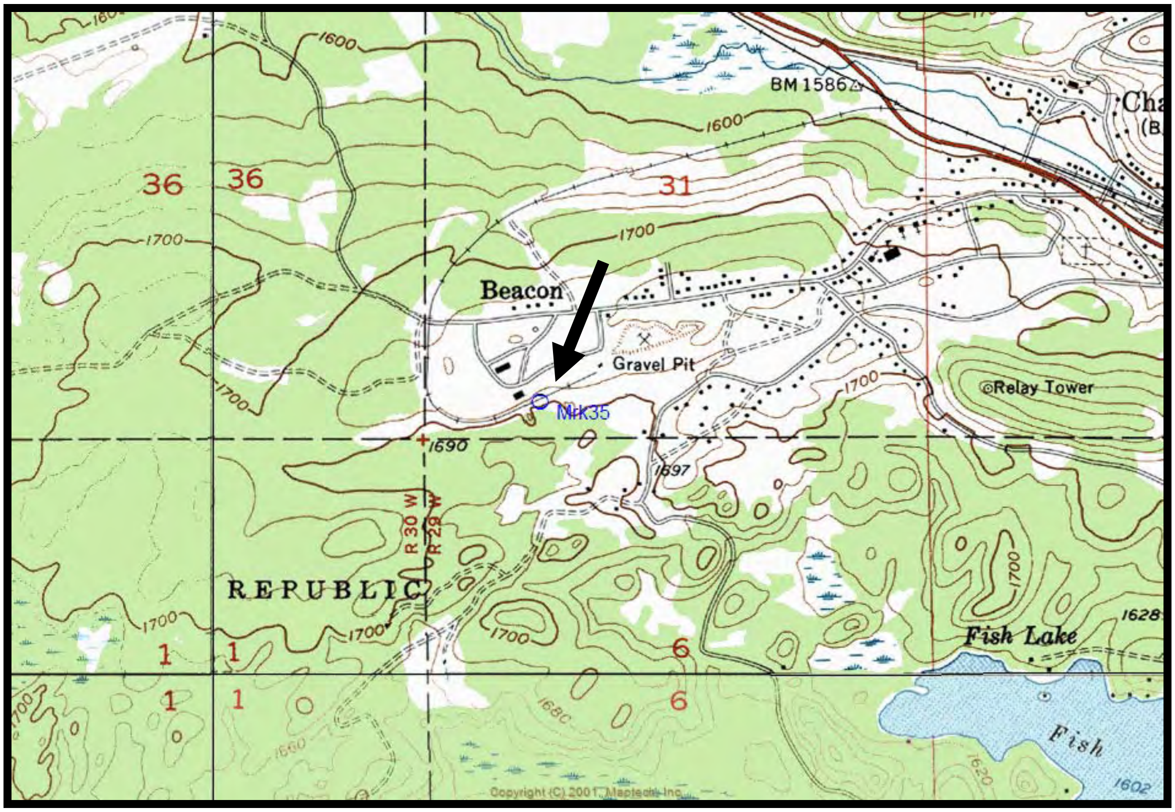

Figure 8-1 Champion Mine

The Champion Mine provides an excellent example of coarse specularite and magnetite hard ore similar to that found in the Humboldt, the Greenwood and the Republic Mines. Even though Babcock (1966, 1974) identified over 70 minerals at Champion, only the most common are available.

The Champion Mine was operated spasmodically by multiple operators for over 100 years (1867-1967) and produced 6.5 million long tons of combined coarse specular hematite (fig. 58) and magnetite (fig. 59). The mine was accessed from seven shafts numbered progressively from east to west (see fig. 60 longitudinal section). The ore body is irregular, thin and dips 78 degrees to the north-northwest. The spindle shaped ore shoots rake steeply to the southwest. The lower level (26th) is at 2100 feet below the collar of shaft #7. Generally specular hematite occurs near or at the hanging wall Goodrich quartzite contact. In some cases iron ore has replaced some the overlying quartzite. Magnetite is more common on the footwall side and with increased depth. The iron formation is approximately 400 feet thick throughout the mine. Oxygen isotope studies have indicated iron oxides formed at 400-500°C.

The original mineral composition of the banded iron formation is impossible to determine but we know the magnetite-silicate-chert was subjected to alteration that started with the formation of sericite and chlorite themselves replaced by specularite and magnetite respectively. Some of the magnetite postdates the specularite. Tourmaline and quartz followed while the last major addition included: quartz, jacobsite, manganese iron silicates, gold, pyrite (fig. 61), chalcopyite, bismuthinite, molybdenite and scheelite. Bodwell (1972) indicated the late mineral stage was prevalent between the #5 and #7 shafts associated with multiple quartz veining in massive magnetite.

Alteration minerals are many but only a few are readily recognizable. Among them are: chloritoid, andalusite (fig. 62), andradite (fig. 63), garnet, tourmaline (fig. 64), sericite and chlorite. The manganese addition can be found in the minerals: jacobsite, mn-chloritoid, spassertine, kutnohorite, mn-cummingtonite, pyrophanite and mn-actinolite. L. Babcock's studies of the mineralogy, using samples collected in the mine and from the dumps, reported the presence of gold. One 2 foot intersect in a diamond drill hole assayed 0.198 ounces per ton. Dump samples consisting of garnet-chloritoid-sulfides and massive magnetite with sulfides can assay 1-2 ppm gold. In some parts of the mine greisen has developed that contain visible molybdenite (fig. 65) that assays above 1% Mo. Subsequent workers have compared the Champion FeOx gold occurrence to the Tennant Creek and Starra deposits found in Australia. Taken by itself it could be just an anomaly, but coupled with widespread late sulfides associated with range wide hard ore, elevated hard ore REE values, the presence of copper and tungsten found on the south limb of the Republic trough and the presence of ferrites would suggest the iron formation and subsequent hydrothermal alteration are distal end products of a possible remote Iron Oxide Copper Gold (IOCG) feeder system (s). The high level metamorphic assemblage found at the Champion Mine is not seen in the surrounding sedimentary or volcanic rocks indicating the high grade metamorphic rank is site specific and not regional in nature.

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54th Annual Institute on Lake Superior Geology

FIELD TRIP 2

ARCHEAN-PALEOPROTEROZOIC UNCONFORMITY AT SILVER LAKE--SEISMITES FROM THE SUDBURY IMPACT?

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Shattered Archean granite with matrix of clastic sediments overlain by Paleoproterozoic argillite with soft-sediment flow structures---products of intense seismic shaking?

Introduction

The Silver Lake area (Figure 2.1) lies along the north margin of the Dead River Basin, a structural outlier of Paleoproterozoic strata surrounded by Archean crystalline rocks. Silver Lake, a natural water body, was enhanced by an impoundment constructed in 1910 and served as a storage basin for downstream hydroelectric generation along the Dead River. Small outcrops along the north shore of the enhanced lake showed a variety of interesting and puzzling features at the Archean-Paleoproterozoic unconformity (Klasner and others, 1979). In May 2003, after very heavy rains, a segment of an earthen dam failed, resulting in catastrophic flooding downstream and a drop of the lake to near the original natural level. The current lake level is 25 to 30 feet below the former impounded level and about 1,000 acres of the previous lakebed are now dry land. This has resulted in reemergence of numerous outcrops on the former lake floor. These outcrops are along the Archean-Paleoproterozoic unconformity and are the focus of this trip. Because reconstruction of the dam and subsequent reflooding of the basin are planned, there is only a narrow time window in which to observe and study these unique features.

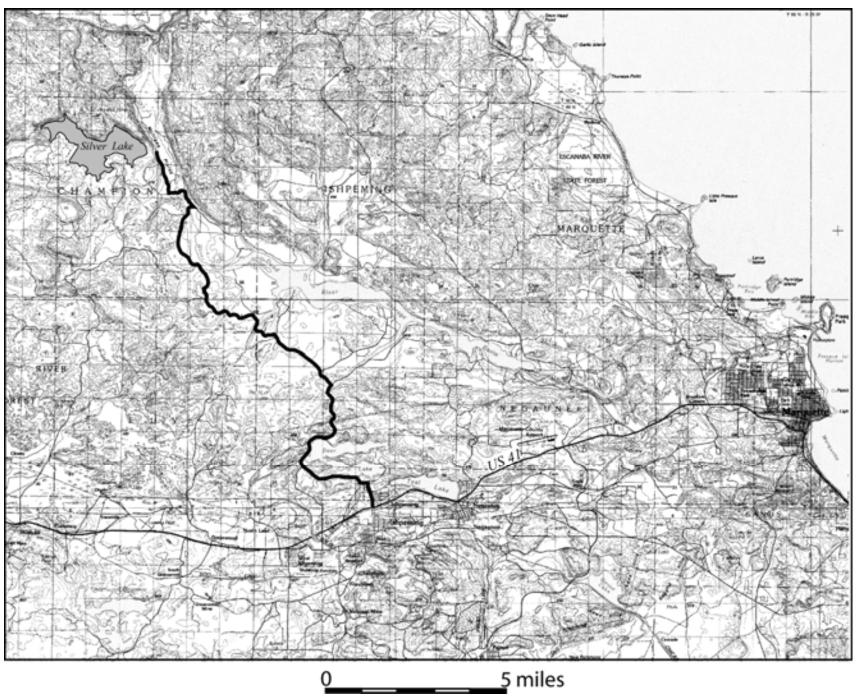

Figure 2.1. Map of the Marquette region showing the location of Silver Lake and the driving route north from U.S. Highway 41 in Ishpeming.

General Geology

The Silver Lake area lies on the northern flank of the Dead River basin, which is a structural basin filled with Paleoproterozoic sedimentary rocks and surrounded by Neoarchean crystalline rocks of diverse lithology. The geology of the basin was mapped in detail during the 1970's (Puffett, 1974; Clark and others, 1975; Klasner and others, 1979). The Paleoproterozoic rocks consist entirely of various informal units of the Michigamme Formation, a part of the Baraga Group. The Michigamme is volumetrically dominated by a thick succession of turbidites, which form the upper part of the formation. The lower units, however, including those seen at Silver

Lake, consist of quartzite and conglomerate, laminated argillite, carbonaceous shale, and lean iron-formation or ferruginous chert. Recent studies also identified a layer of ejecta-bearing rocks in the lower part of the formation, which has been correlated with the Sudbury impact event (Cannon and others, 2006a, b; Cannon and Addison, 2007a, b; Kring and others, 2006; Pufahl and others, 2007).

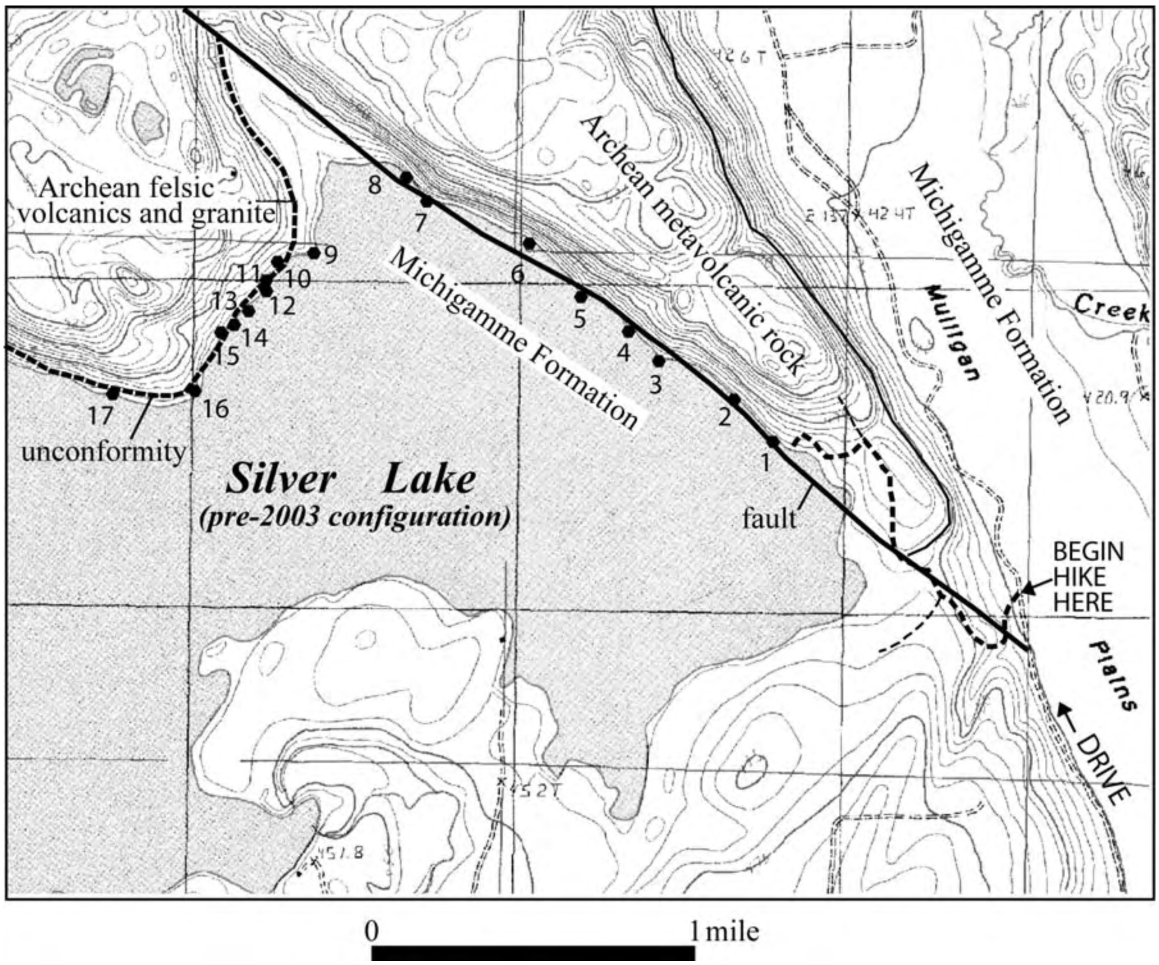

Figure 2.2. Map of the Silver Lake field trip area showing localities (1 through 17) described in this guide. General geologic relationships are generalized from Klasner and others (1979). The heavy dashed line is an unmaintained logging road drivable in some seasons by the stout of heart. This trip will hike the road from the point indicated. The extent of Silver Lake as shown is that prior to the 2003 dam failure. It's configuration in 2008 is much smaller than shown.

The structure of the Dead River Basin basin is complex as a result of both Penokean and Yavapai deformation. During the Penokean orogeny, between 1850 and 1830 Ma, thin-skinned deformation produced folds and slatey cleavage that are best developed in the upper part of the Michigamme. None of the structures seen at Silver Lake can be definitively assigned to the Penokean orogeny. The present structural basin is a result of differential movement between fault-bounded blocks of Archean rocks and the molding of Proterozic strata around the fault blocks. This deformation has long been interpreted to be a late phase of the Penokean orogeny, but recent geochronological data suggest that it is younger and equivalent in age to the Yavapai orogeny at appxoximately 1775-1750 Ma (see recent summaries by Holm and others, 2007; Schulz and Cannon, 2007). A low-temperature regional hydrothermal event has been documented to have occurred at nearly this same time during which xenotime cements formed in the basal Michigamme Formation. Such secondary xenotime is well developed at Silver Lake and material collected from Locality 16, described below, yielded a xenotime crystallization age of approximately 1785 Ma (Vallini and others, 2007).

The geology in the area of this field trip is shown in Figure 2.2. Archean rocks, a diverse suite of metavolcanic and granitic rocks, form the prominent uplands whereas the Michigamme Formation underlies the lowlands. The very steep hillsides reflect the extreme contrast in erosional resistance of these two units. The area is divided into two structural panels by a prominent fault along the northeastern shoreline of Silver Lake. Northeast of the fault, Archean rocks are relatively uplifted and tilted toward the northeast. Along the steep hillside descending onto the Mulligan Plains there are sporadic exposures of the basal beds of the Michigamme Formation which dip 40° northeast and thus indicate the amount of rotation. Foliation in outcrops along the fault is nearly vertical.

Southwest of the fault, including the area that is the focus of this trip, a block of Archean rocks has been uplifted and tilted slightly toward the southwest so that the unconformity between it and the Michigamme Formation forms a gently southeast-dipping surface along the lakeshore in the northwestern part of Figure 2.2. Draining of the lake exposed extensive new outcrops, such as shown in Figure 2.3, that consist of Archean rocks, mostly massive to foliated granite, and the basal beds of the Michigamme Formation. The outcrop surface closely mimics the unconformity surface so that discontinuous patches of the Michigamme are preserved in declivities on that surface.

Lithology of basal Proterozoic beds. The maximum thickness of the preserved Paleoproterozoic strata at the field trip stops is only about one meter. A variety of rock types from conglomerate to fine-grained laminated sedimentary rocks are present and the rock type at any particular locality may reflect the micro-topography along the surface at the time of deposition. A few lenses of pebble conglomerate appear to be somewhat mature and consist of rounded and obviously water-worked debris, including rounded quartz pebbles. These may be lenses of wave-washed gravel that accumulated in depressions on the Archean surface during the earliest phase of marine transgression. More typically, basal beds are breccia consisting almost entirely of angular fragments of rock types contained in the immediately underlying Archean basement. They may be a residuum of physically weathered basement rock that experienced little or no wave action. Laminated fine-grained sedimentary rocks also are widespread and occur both above the basal conglomerate lenses or lie directly on the Archean basement where basal conglomerate is absent.

Figure 2.3. Area near Location 17 showing the newly exposed outcrops of the former lake bottom. The land surface very closely mimics the unconformity between Archean granitic rocks and basal beds of the Michigamme Formation. Hundreds of individual vestiges of the basal sediments dot the surface of the granite.

A significant aspect of the lowermost sediments is phosphatic material that occurs as masses of nearly pure carbonate flourapatite. These masses are typically from a few to as much as 10 cm in diameter and some have shapes and internal structures suggestive of stromatolitic growth. These were first described by Cannon and Klasner (1976) along with numerous other occurrences of phosphatic material within basal Baraga Group rocks in the Marquette area. A good example of these is shown in Figure 2.4A where stromatolite-like growths of apatite have repeatedly developed in the lowermost few centimeters of the Michigamme Formation immediately adjacent to the unconformity with Archean rocks and occur in three or four individual layers separated by fine-grained clastic sedimentary rocks. In this particular case, microtopography along the unconformity appears to have localized growth on a banded quartz vein which stood in relief above the surrounding granite. Phosphate masses grew on the relatively steep surface of the quartz vein, a situation apparently in some way physically favorable for phosphate accumulation. Other phosphate masses, such as shown in Figure 2.7B, occur directly on the unconformity with Archean granite. Some of this phosphatic material was also reworked into overlying conglomerate lenses.

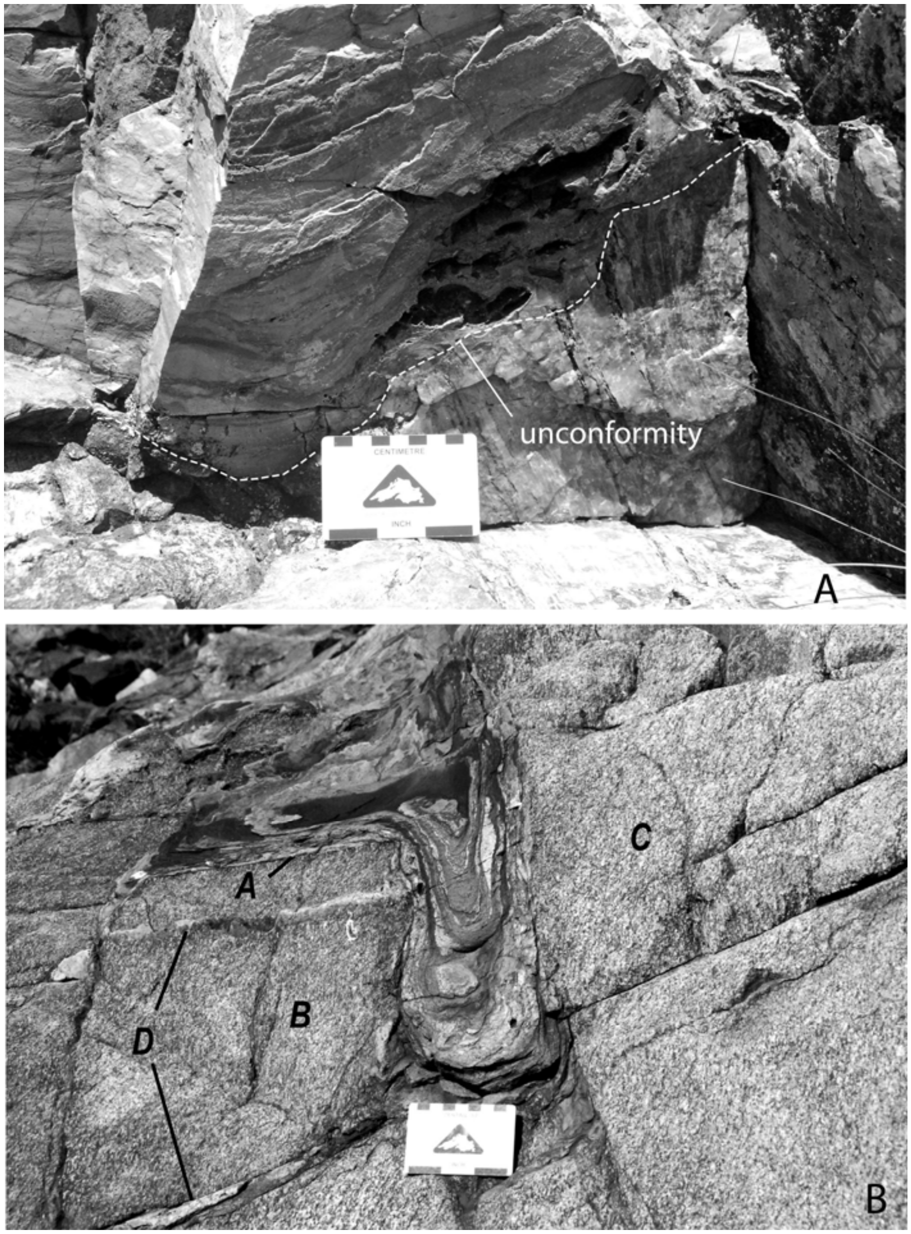

Figure 2.4. A- Masses of carbonate flourapatite (dark areas of negative relief just above unconformity) that appear to have grown in successive layers along steeply dipping microtopography on the unconformity. Host beds are laminated argillite. The immediately underlying rock is a banded quartz vein that cuts Archean granitic rocks. This feature can be seen at Locality 11.

B- Small fold of Michigamme argillite between blocks of Archean granite. A vestige of the unconformity is seen at point A where the argillite was deposited in flatlying bedns on the Archean. The space not occupied by the fold was created by lateral opening of a gap between granite blocks B and C and slumping of the soft sediments into the new space. Other joints in the granite (D) are filled with injected sediments. Feature can be seen at Locality 16.

Structure

The excellent exposures created by the draining of Silver Lake reveal a set of unusual, intriguing, and puzzling small-scale structures along the unconformity. The gross structure is simple. The unconformity seen at localities 9 through 17 is gently inclined toward the south and southeast as a result of rotation of the Archean basement rocks, probably in the time interval 1775-1750 Ma. There are no penetrative fabrics within the Archean rocks that can be ascribed to this period of deformation; rather the Archean appears to have moved as a series of rigid blocks separated by faults and the overlying Paleoproterozoic strata moved passively with them.

A variety of small-scale structures are also well exposed and appear to record an unusual structural event that we propose might have been a powerful earthquake caused by the giant Sudbury impact event. At several nearby localities within the Dead River Basin, a layer of ejecta-bearing breccia, interpreted to have been formed by the Sudbury impact is within the lower part of the Michigamme Formation (Cannon and others, 2006a, b; Kring and others, 2006; Cannon and Addison, 2007a, b; Pufahl and others, 2007). There is clearly a close temporal correspondence with the basal Michigamme beds exposed at Silver Lake and the time of the impact. In fact, our preliminary petrographic study of these rocks, discussed more fully below, found features that might be directly caused by the impact. Two types of structures are present: 1) drapes of Michigamme sediments around Archean blocks that have undergone small displacements relative to each other, and injection of sediments into joints within the Archean basement; 2) intense brecciation of the Archean rocks, soft-sediment flow of the basal Michigamme and intermixing of the two rock types.

The first type of features, drapes of sediment around Archean blocks, is best seen at localities 14 through 17. Figure 2.4B shows the essential characteristics of this type of deformation. Fine-grained laminated sediments were deposited unconformably on Archean granite in essentially flat-lying beds. This unconformiable surface is widely preserved (such as at A in Figure 2.4B). The tight syncline shown in figure 2.4B formed as these flat-lying sediments slumped and flowed into an open space created as blocks of granite (B and C) separated laterally. Numerous joint surfaces (D in Figure 2.4B) are also filled with sediments which apparently flowed into open spaces during this same event. Individual granite blocks ranged up to several meters or tens of meters in diameter and experienced relative displacements up to several meters. The result is a complex unconformity surface with structural relief of meters and complexly folded basal Michigamme strata.

The second type of feature, brecciation of basement rocks and soft-sediment flow of the basal Michigamme, is very well displayed at localities 9 through 13 and illustrated in Figure 2.6 (Locality 9). All stages of brecciation of basement rocks are preserved, ranging from small movements on joint surfaces and infilling of the spaces thus created by sediments (Figure 2.9; Locality 13) to intense dismemberment of the Archean rocks into angular fragments which are intermixed with a matrix of clastic sediments (Figure 2.8; Locality 13). In the less brecciated granitic basement, clastic dikes are very common and range in thickness from nearly a meter to a few millimeters. The wider dikes commonly have an internal lamination (Figure 2.7A for example; Locality 11) indicating that the sediment fill was caused by an injection of originally overlying laminated sediments rather than an infiltration of individual clastic particles into open space. In places (locality 13 for example) a remarkable intersecting array of clastic dikes extends at least several meters below the unconformity showing that sediments were able to completely infiltrate a joint system well below the unconformity. Such features imply that a period of dilation affected the Archean rocks during which overlying soft sediments were injected into all available open spaces.

Sudbury Seismites?

Could the array of unusual features seen at Silver Lake have been caused by intense seismic shaking, and could that shaking have been caused by the giant impact at Sudbury? Giant impacts do generate exceptionally powerful earthquakes. For instance the Chicxulub impact in Mexico has been variously estimated to have generated a quake of M 10 to13 on the Richter scale, significantly more powerful than the largest known terrestrially generated earthquake. The Sudbury impact was a somewhat larger event. It too should be expected to have generated an earthquake of nearly unprecedented energy and to have left a unique imprint on rocks of the region. A calculation of the seismic intensity from the Sudbury impact using the on-line Earth Impact Effects Program (Marcus and others, 2004) indicates an intensity of 10.5 on the Richter scale, greater than any earthquake in recorded history, and a Mercalli Scale Intensity of X at Silver Lake (nearly total destruction of man-made structures in the modern sense). The Chicxulub impact has been shown to have produced seismic disturbance of sediments well over a thousand kilometers from the impact site (Norris and others, 2000; Terry and others, 2001). Thus it seems likely that the Silver Lake area, only about 500 km from Sudbury, was well within the range of significant seismic disturbance from the Sudbury impact.

The intense shattering of Archean basement rocks and contemporaneous flow of overlying soft sediments are features that could have been caused by the passage of an impact-generated shock wave and consequent shaking. The complex array of sedimentary dikes that cut the Archean require a period of dilation during which fractures in the granite were opened and then filled by the injection of overlying soft sediments. Such features can form during passage of a seismic wave in which the leading edge of the wave is compressional and is followed by a dilational wave (Melosh, 1989). During this instantaneous dilation the Archean rocks may have expanded and formed open spaces along fractures. Overlying sediments would have been injected into the newly created space. Similar features have been reported from the Locke impact structure in Sweden (Sturkell and Ormo, 1997) where sediment dikes cut shattered granitic rocks surrounding this small Ordovician crater. Some of the material at Silver Lake is also similar to “clastic Sudbury breccia” (Rousell and others, 2003) that is found as much as several tens of kilometers outside of the present Sudbury Basin.

A final piece of evidence that suggests a possible link to the Sudbury impact is possible impact-related grains that have been found in some of the clastic dikes. Although our petrographic examination is very preliminary at this point, we have observed numerous millimeter-scale round to ovoid grains consisting of very fine-grained brownish clay. Many have abundant shrinkage cracks (Figure 2.5). These are very similar in appearance to grains that occur in some phases of the Sudbury impact layer at nearby occurrences and have been interpreted as altered microtectites formed from impact-generated vapor. These same rocks also contain a sparse collection of quartz grains that have planar features that may be shock-induced planar deformation features (Figure 2.5D), but we have not yet found truly definitive shock features. Nevertheless, there is at least suggestive evidence that ejecta material from the Sudbury impact was incorporated into the clastic injections. The distance which the Sudbury layer lies above the stratigraphy exposed at Silver Lake is unknown but it could have been very small. The nearest known exposure, Connors Creek, is only about 3 km to the south. There the Sudbury layer is about 150 meters above the Archean unconformity. Regional relationships suggest that underlying strata thin to the north and the layer may be very close to the level exposed at Silver Lake. Thus, we propose a model in which Sudbury ejecta material arrived at Silver Lake essentially contemporaneously with severe seismic shaking and deformation of Archean rocks that were overlain by only a meter or two of Paleoproterozoic sediments at the time. Both the sediments and ejecta particles were emplaced as sediment dikes in newly opened fractures.

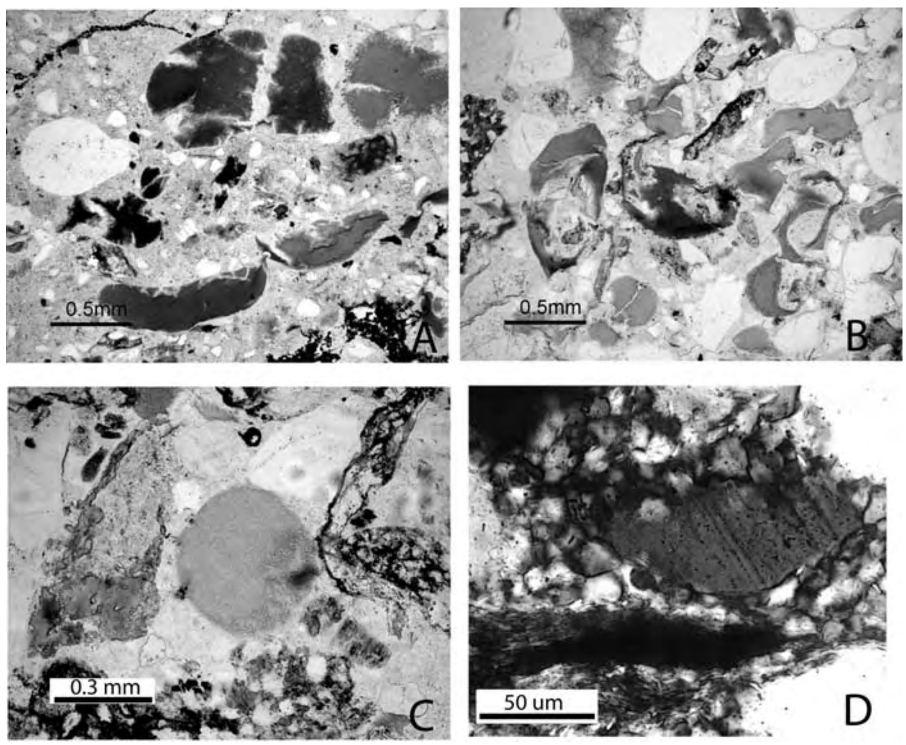

Figure 2.5. Photomicrographs of clastic material from sediment dikes injected into the Archean basement rocks. A, B- Broken and distorted spherules of aphanitic brown clay in siliceous fine-grained matrix containing abundant quartz sand grains. These spherules are very similar in appearance to spherules within Sudbury ejecta deposits nearby. C- intact spherule of aphanaitic clay. D- quartz grain cut by planar features the may be shock induced planar deformation features.

FIELD TRIP LOCALITIES

The localities of principal interest for this trip are numbers 9 through 17 as shown on Figure 2.2. The easiest walking route to these localities is along the old shoreline on the northeast side of Silver Lake. Along this route numerous outcrops (localities 1 through 8) lie along the fault that juxtaposes Archean basement rocks and the Michigamme Formation. The route crosses the fault several times so exposures of both the Archean basement and Michigamme Formation can be examined. These eight localities are described briefly and localities 9 through 17 are described in more detail. Latitude and longitude values are given for each locality to assist in GPS navigation to them. In general, the photographs shown in Figures 2.6 through 2.11 are taken within a few tens of feet of the GPS locations.

Locality 1.-- (46.6603, -87.8134) Small outcrop of sheared quartz and plagioclase phyric rhyolite; part of Archean basement.

Locality 2.-- (46.6614, -87.8149) Long outcrop (300 ft) of massive to weakly foliated Archean biotite amphibolite. Foliation is irregular. Some features may be relict pillow selvages or cryptic pillows. The southeasternmost part of the outcrop is highly sheared, probably by movement on the fault.

Locality 3.-- (46.6625, -87.8180) Michigamme Formation. Rusty-weathering, dark gray to black slate. A steep uniform cleavage is very well developed. In places bedding laminations from ½ to 1 inch thick are parallel or subparallel to cleavage.

Locality 4.-- (46.6632, -87.8192) Michigamme Formation similar to Locality 3, except there are beds of coarser, more massive greywacke toward the north side of the outcrop.

Locality 5.-- (46.6642, -87.8213) Michigamme Formation similar to locality 3.

Locality 6. -- (46.6656, -87.8234) Long outcrop (300 feet) of highly sheared mafic volcanic rock (Archean). Way point is at northwest end of outcrop.

Locality 7.-- (46.6667, -87.8273) Michigamme Formation as at Locality 3.

Locality 8.-- (46.6674, -87.8282) Sheared Archean amphibolite with lesser felsic layers. Coarse amphibole crystals in places. Layering is parallel to nearly vertical shear foliation.

Locality 9.-- (46.6652, -87.8319) After leaving locality 8 and turning southwest the route passes onto the Archean basement block south of the fault that has been tilted gently to the southeast. The unconformity with the base of the Michigamme Formation is well exposed here as a surface that dips about 15° to the southeast. The Archean rocks are sheared felsic metavolcanics with nearly vertical compositional layering and shear foliation (Figure 2.6A). They are overlain by a layer of breccia only an inch or two thick. Clasts are mostly very angular and appear to be in very large part of the same lithology as the immediately underlying Archean rocks (Figure 2.6B). Laminated gray argillite overlies the basal breccia. Only the lowest foot or two of this unit is exposed here. The relationships shown here leave no doubt that the intense penetrative deformation in the Archean rocks entirely pre-dates deposition of the Michigamme Formation.

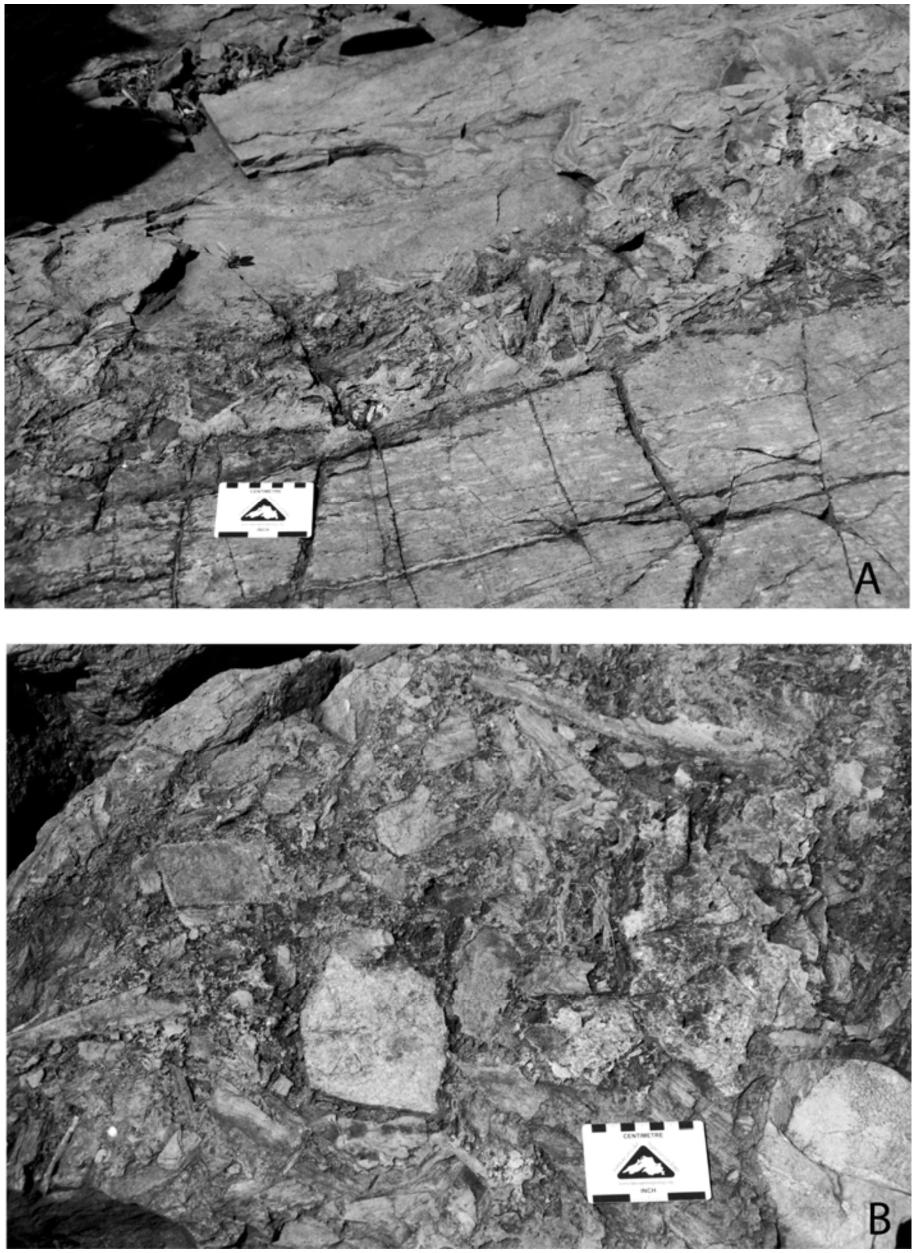

Figure 2.6. Features seen at Locality 9. A- unconformity between sheared Archean felsic volcanic rocks below and gray laminated argillite of the Michigamme Formation above. The base of the Michigamme Formation consists of a few inches of conglomerate with very angular fragments, mostly with lithology identical to the immediately underlying Archean rocks. The surface is cut obliquely through the strata which exaggerates the apparent thickness of the basal conglomerate bed. B- closeup view of the basal conglomerate showing the extreme angularity of most clasts and the essentially unsorted nature of the bed.

Locality 10.-- (46.6649, -87.8333) Rocks here are entirely Archean and are mostly laminated metasedimentary rocks in beds ½ to 1 inch thick. Beds are highly folded and fold axes plunge about 55° to the southeast. The north edge of the outcrop is a sheared mafic rock, possibly a dike intruded into the metasedimentary unit.

Locality 11 (46.6649, -87.8338) and Locality 12 (46.6642, -87.8337).-- These two localities are on the north and south ends respectively of a large outcrop area. Near locality 11, on the north part of the outcrop, a thin skin of basal conglomerate lies on the Archean basement. In places the Archean foliated granite is broken into large blocks and open spaces between the blocks are filled with sediment and small angular granite fragments. Lamination in the sediments is preserved in part and was deformed against the granite blocks (Figure 2.7A). At several places along the unconformity, light gray aphanitic masses of carbonate flourapatite lie directly on the granite (Figure 2.7B). Toward the south end of the outcrop, near Locality 12, one to two feet of breccia forms a layer down the east side of the exposure. This differs from most of the other nearby basal conglomerates in having a quartz-chlorite matrix and a diversity of lithic fragments of Archean rocks, including chert and quartz pebbles. Is some of this material Subury ejecta? The southern end of the outcrop is Archean granite.

Locality 13.-- (46.6636, -87.8345) The outcrops here show the best examples of intensely brecciated Archean rocks, soft-sediment deformation and flow of Michigamme argillite, and intense development of sediment dikes in the Archean basement. On the northside of the outcrop the Archean rocks are brecciated to highly variable degrees. In places blocks of the Archean have moved apart on joint surfaces to create open space that was filled by clastic sediments. All variations can be seen from this relatively mild deformation to complete shattering of the Archean into centimeter-scale angular fragments that are suspended in a clastic matrix (Figure 2.8B). In some cases adjacent fragments can be fitted together to reconstruct the pre-brecciation geometry indicating that fragments have not moved far during the brecciation process. The unconformity is also well exposed here. Rather than a basal conglomerate, the base of the Michigamme is laminated argillite. Black to pinkish gray color banding emphasizes the bedding and readily shows intense soft-sediment deformation features (Figure 2.8A). There is an intermixing of the Michigamme argillite and Archean granite; granite fragments are incorporated into the basal foot of the sediments and masses of the argillite occur within the upper foot or two of the breccia. We interpret these relationships to indicate that the brecciation and soft-sediment deformation occurred simultaneously in response to the same seismic event.

The south side of the outcrop provides a cross section of the upper 3-4 meters of the Archean basement granite below the unconformity. A remarkable array of sedimentary dikes is seen here at scales varying from about 0.5 m to a few millimeters (Figure 2.9). Virtually every joint surface appears to have a least a thin film of sedimentary material along it. The larger dikes generally have an internal layering shown by variations in grain size that is parallel to the dike margins. Such features indicate that the sedimentary material was forcefully injected into the joints rather than accumulating by settling of grains into open spaces. This in turn implies that there was a dilational event that simultaneously opened all of the fractures in this geometrically diverse fracture system to allow injection of the sediments.

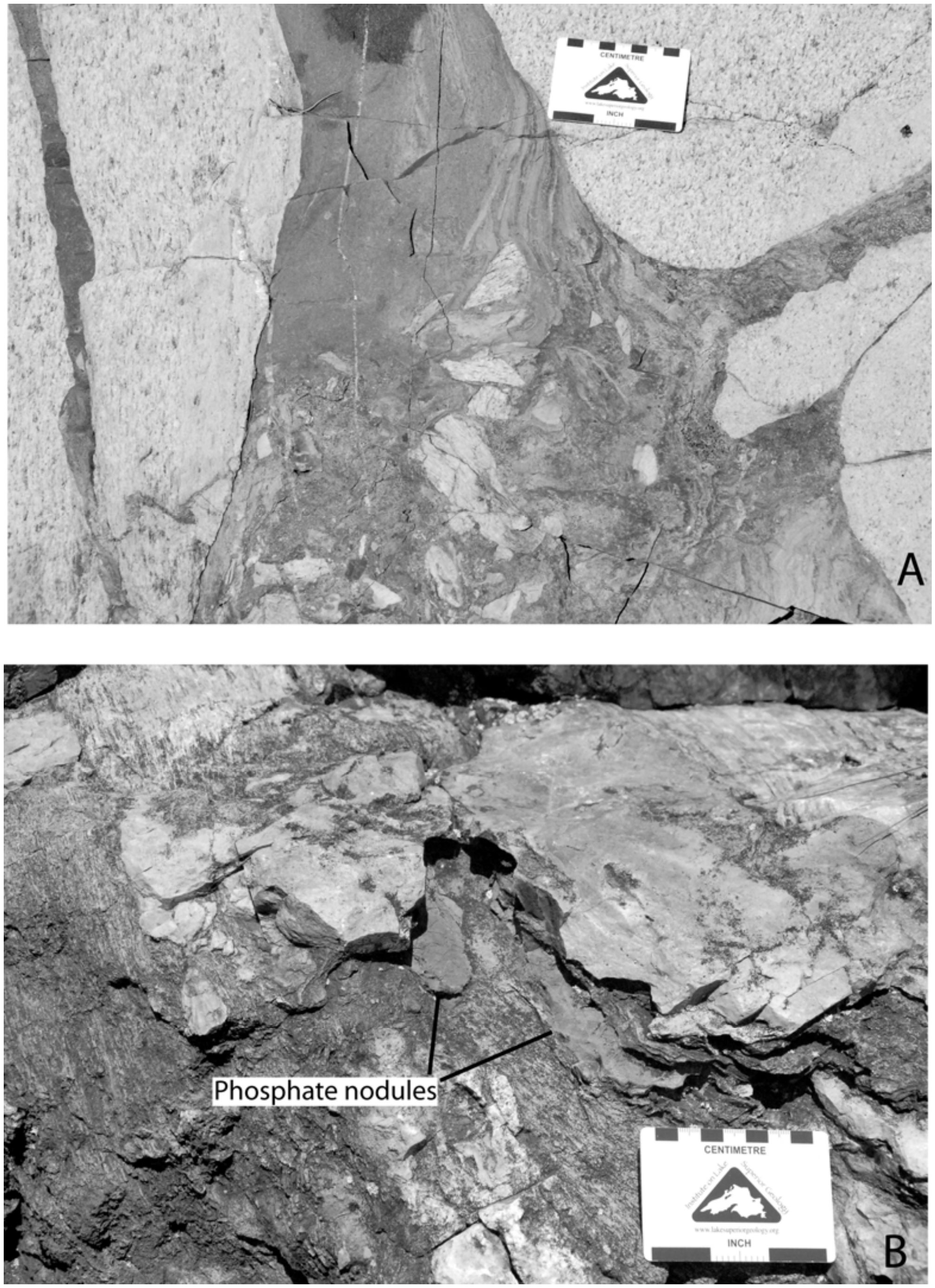

Figure 2.7. Features seen at Locality 11. A- Fractured Archean granite with gray laminated argillite injected between granite blocks. Numerous fragments of the country rock granite are incorporated into the argillite. B- View looking down on the surface of the unconformity. Archean rock is foliated granite. Several masses of carbonate flourapatite are directly on the unconformity surface and are overlain by gray argillite.

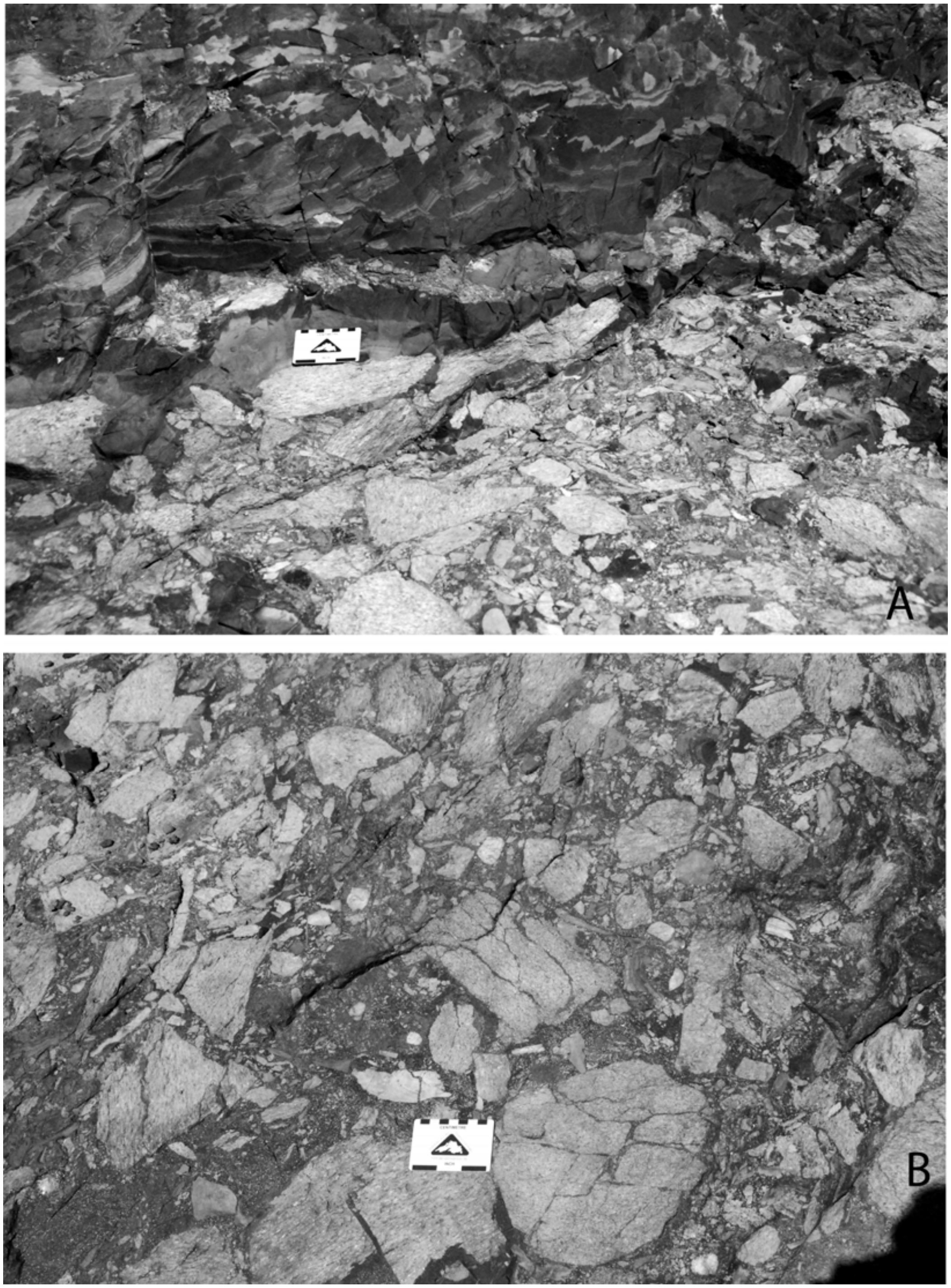

Figure 2.8. Features seen at Locality 13. A- intensely brecciated granite. Angular granite clasts are suspended in a clastic sedimentary matrix. Overlying banded argillite is intensely deformed by soft-sediment flow. Note fragments of granite intermixed with basal beds of the argillite, and masses of argillite scattered through the granite breccia. B- brecciated granite showing varying degrees of fragmentation. Note rounded clast to right of scale with only slight separation of fragments and fractures filled with clastic sediment. Elsewhere angular clasts of various sizes are suspended in a clastic matrix.

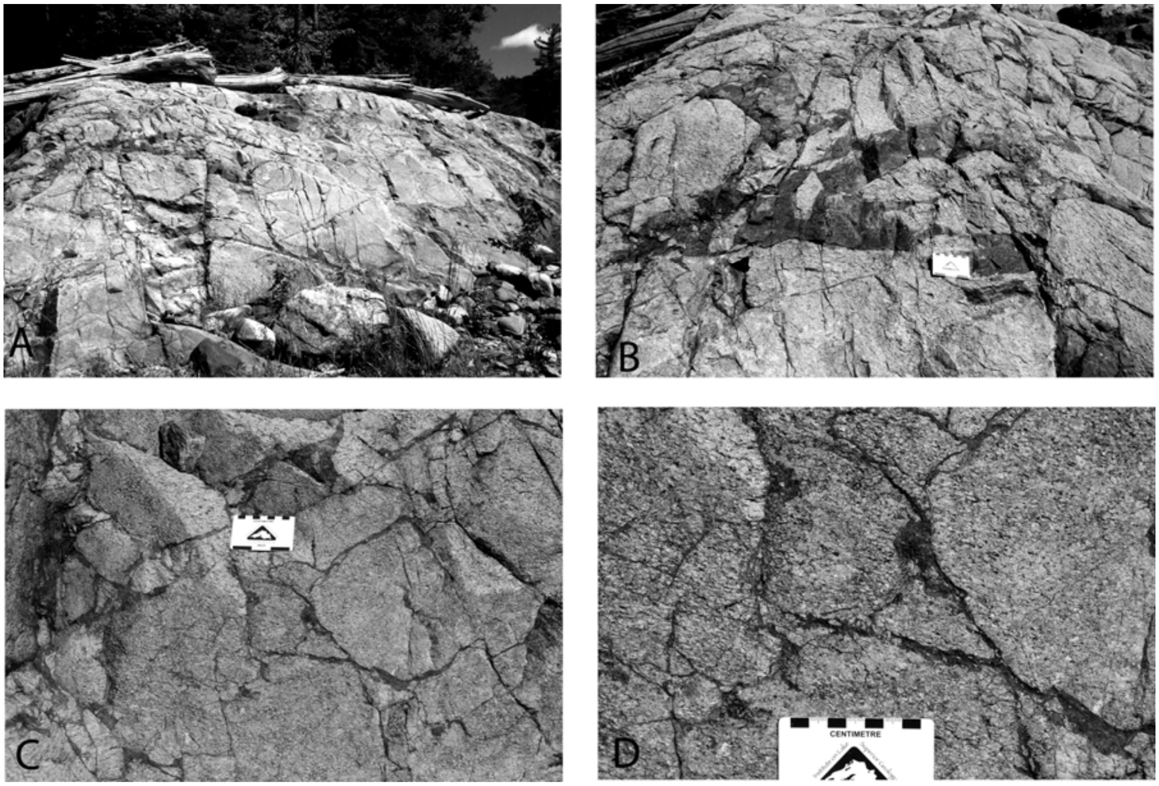

Figure 2.9. Features seen at locality 13. Views of the south side of the outcrop at various scales. The surface of the unconformity exposed on the north side of the outcrop projects to just above the top of the outcrop in A. Note the abundance if sedimentary dikes (darker), throughout the massive Archean granite. Dikes vary from about 2 feet wide (near top of outcrop in A) to paper thin seams (D).

Locality 14.-- (46.6632, -87.8351) At this locality we begin to see a transition in the type of deformation from the brecciation and dike injection to the north to differential movement of larger Archean blocks, ranging in size up to tens of meters, and molding of soft sediments around these blocks. Although sediment dikes and brecciation are still fairly well developed here, there are also several examples of folds in the Michigamme where the sediments have been molded around or compressed between joint blocks of Archean granite. Note that where the basal Michigamme sediments are tightly folded the foliation in the adjacent Archean rocks is unaffected by the folds indicating that the Archean rocks moved as rigid blocks and the Michigamme was molded to the new shape of the top of the Archean. These features are very well exposed at Localities 16 and 17 to the south.

Locality 15.-- (46.6630, -87.8355) This outcrop is entirely Archean rocks, mostly massive granite. On the north end of the outcrop there are many thin sediment dikes but their abundance diminishes to the south.

Locality 16 (46.6613, -87.8365) and Locality 17 (46.6613, -87.8398).—Beginning in the vicinity of Locality 16 and continuing westward to Locality 17, the western limit of good exposures, there are a multitude of small-scale folds in the basal beds of the Michigamme Formation. These are mostly synclinal features with diverse orientations and plunges (Figures 2.10 and 2.11). They appear to have formed as the soft sediments were molded around blocks of Archean rocks as those blocks were structurally rearranged. Note numerous instances where tight folds in the Michigamme have no expression in the immediately adjacent Archean rocks, showing that the folds have formed in response to the newly acquired shape of the unconformity surface on top of the Archean by draping over that surface, or in some instances by being injected into open joints.

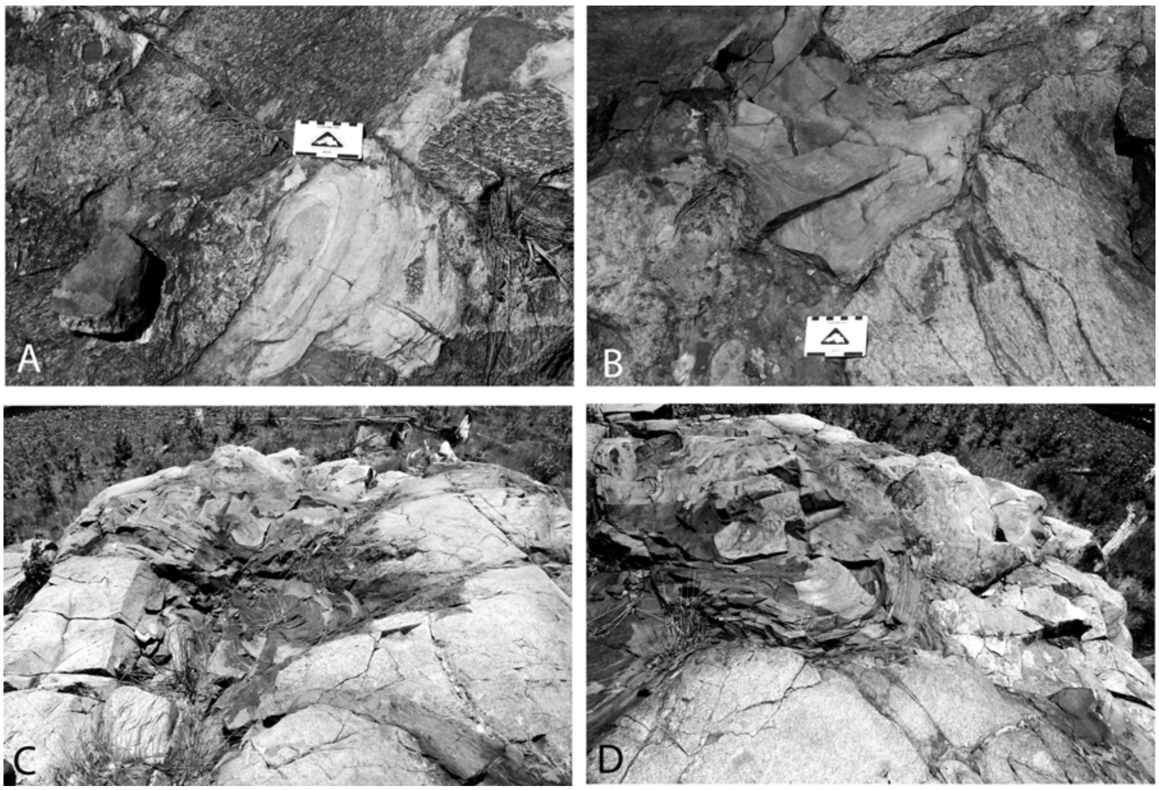

Figure 2.10. Features seen at Locality 16. Examples of small folds in the basal beds of the Michigamme Formation caused by molding the sediments to the shape of blocks of Archean granite. These fine-grained sediments were no doubt deposited in flat-lying beds on a horizontal surface but were later distorted to their present configuration as blocks of Archean rocks were displaced relative to each other.

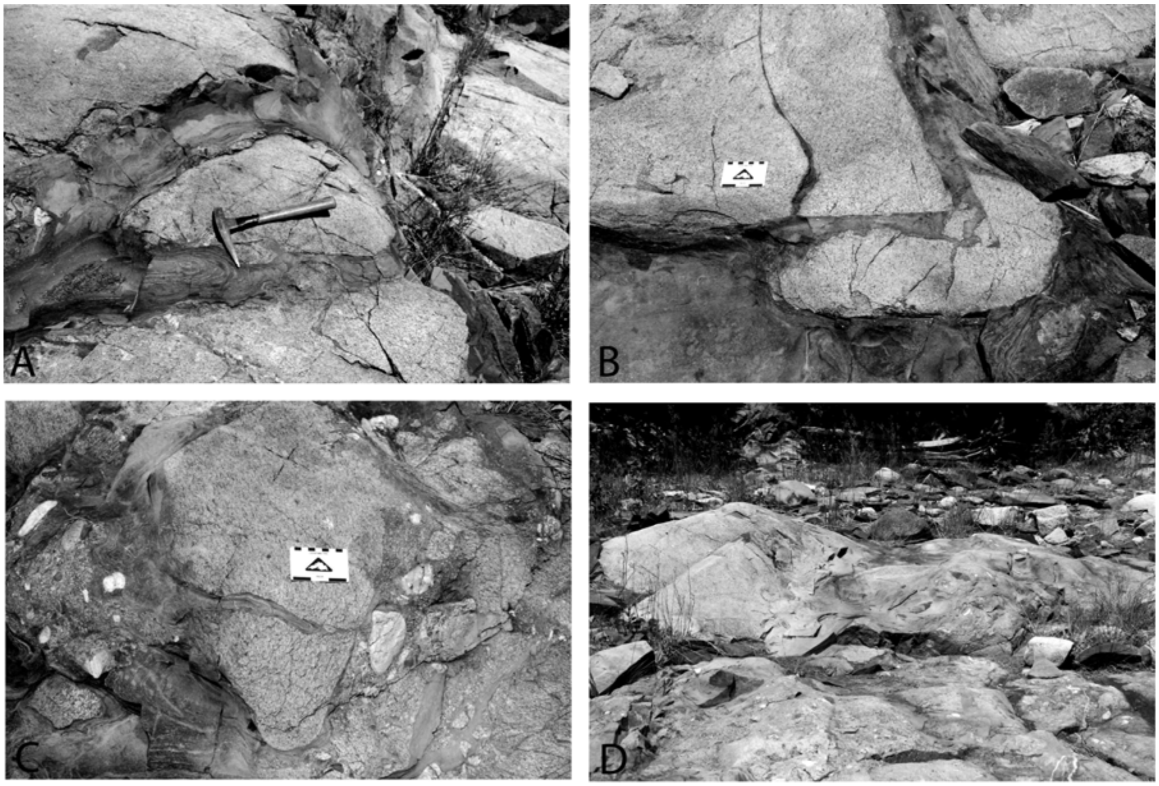

Figure 2.11. Features seem between Localitites 16 and 17. A- synclinal folds of Michigamme Formation argillite with variable plunges formed between blocks of Archean granite. B- Fractures in granite filled with fine-grained sediment. C- fractured boulder with laminated argillite compressed into the open fracture. D- undulating unconformity surface on top of Archean granite with basal Michigamme sediments draped over it.

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54th Annual Institute on Lake Superior Geology

Field Trip 3

GEOLOGY OF THE BACK FORTY PROJECT

Tom Quigley
Bob Mahin

Aquila Field Office Geologic Staff

54th Annual Institute on Lake Superior Geology

FIELD TRIP # 3

Back Forty Geology and Mineralization

Tom Quigley

Bob Mahin

Aquila Field Office Geologic Staff

Gossan mineralization exposed at surface at the Back Forty project site

Introduction

The Back Forty Volcanogenic Massive Sulfide (VMS) deposit located alongside the Menominee River in the Upper Peninsula of Michigan is the most recent deposit of this type found in the Early Proterozoic aged Penokean Volcanic Belt (PVB) which trends east west through Wisconsin and extends into the Upper Peninsula of Michigan. Numerous massive sulfide occurrences and several significant deposits were discovered as a result of protracted exploration efforts focused on the Wisconsin portion of the PVB during the 1960's, 1970's, and early 1980"s including the Crandon deposit (61 million tonnes 5.6% Zn), Flambeau (5.8 million tonnes 4% Cu) and Lynne (6.1 million tonnes 8.7% Zn).

The Back Forty was discovered in 2002, and has a resource (current as of April 2007) of 6.6 million tonnes with 5.3% Zn, 2.3 grams/tonne (g/t) Au, 29 g/t Ag, and 0.5% Cu in the measured and indicated category, and an additional 1.75 million tonnes of 2.6% Zn, 2.8 g/t Au, and 32 g/t Ag in the inferred category, making it the 2nd largest deposit found in the PVB to date and placing it in the upper 30th percentile in size of VMS deposits worldwide.

The April 2007 resource was calculated on the basis of 151 diamond drill holes (35,000 meters). Since then an additional 150 holes (30,000 meters) of drilling has been completed in anticipation of a new resource calculation, preliminary mine design, metallurgical testing, and pre feasibility studies planned for 2008 and 2009.

Regional Geologic Setting of the Back Forty VMS Deposit

The Back Forty VMS deposit is one of a number of similar deposits located within the Ladysmith-Rhinelander volcanic complex in northern Wisconsin and western Michigan. The complex lies within the Early Proterozoic Penokean volcanic belt (PVB), also known as the Wisconsin Magmatic Terrain, on the western edge of the Paleozoic Michigan Basin (Figures 1 and 2).

Figure 1

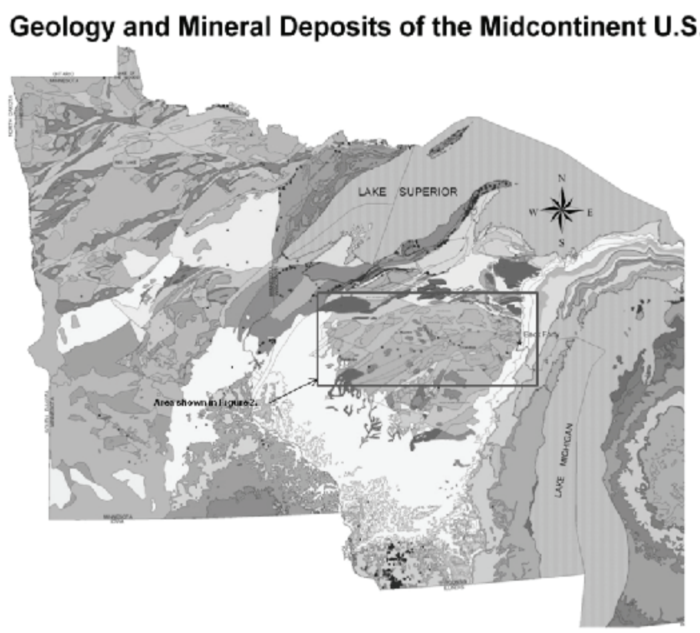
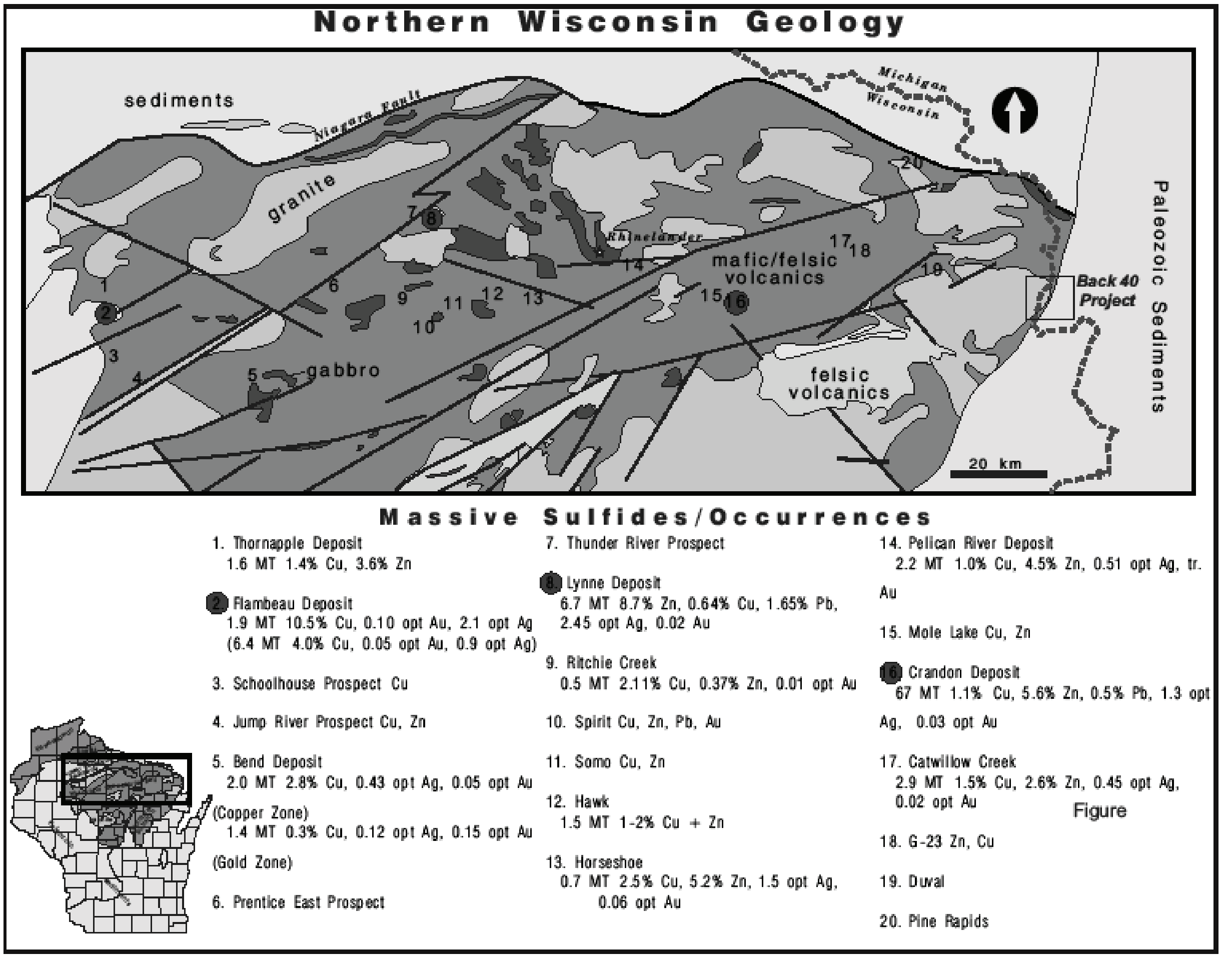


Figure 2. Location of Back Forty project and other major VMS deposits



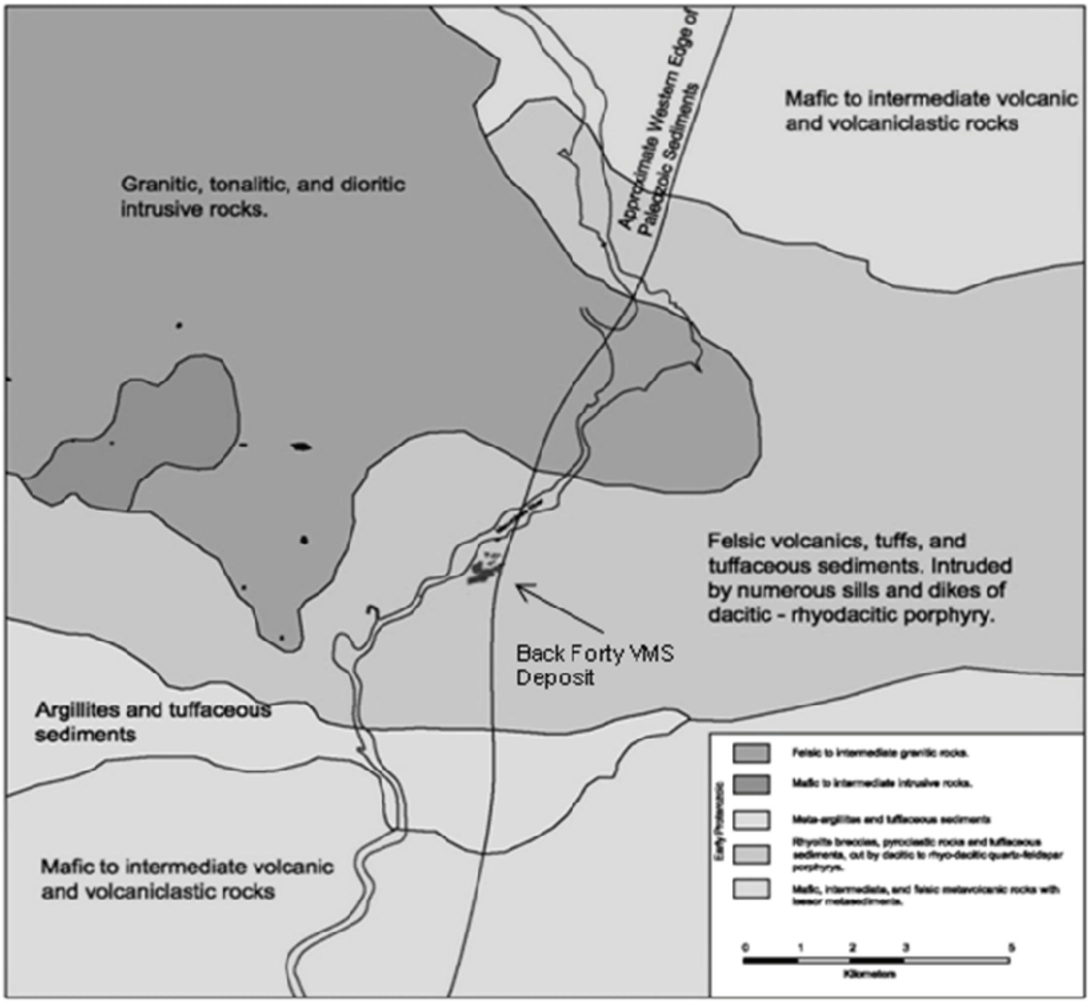
The PVB is characterized by volcanic island-arc-basin assemblages containing abundant calc-alkaline metavolcanic units, intrusive rocks and lesser amounts of sedimentary rocks, and is in structural contact to the north, along the Niagara Fault zone, with a back arc basin sedimentary terrain containing subordinate interbedded tholeiitic metavolcanic rocks and major Superior-type, oxide-facies iron formations. This supracrustal sequence appears to correlate with the Marquette Range Supergroup in Michigan (Dematties 2004).

The Back Forty project is located at the eastern edge of the PVB where the older volcanic supracrustal rocks of the belt are covered by Paleozoic sedimentary rocks of the Michigan Basin.

Local Geologic Setting

Figure 3 shows the interpreted bedrock geology of the Back Forty area derived from published geologic maps, airborne and ground geophysical data and sparse outcrops.

Figure 3. Bedrock Geology of the Back Forty Project area.



Back Forty mineralization is hosted by dominantly felsic volcanic rocks which appear to be spatially and possibly genetically related to a large intrusive complex of granite, tonalite and more mafic phases exposed sporadically in Wisconsin and interpreted to extend into Michigan based on gravity and magnetic data. This central complex of felsic intrusive and volcanic rocks is flanked on the north and south by more mafic volcanic sequences as well as argillites and fine grained tuffaceous rocks to the south.

Deposit Scale Geology

Geology of the host rocks

Back Forty mineralization consists of massive, semi massive, and stringer sulfide mineralization as well as precious metal zones with sparse sulfides, developed within a highly altered sequence of rhyolite breccias and pyroclastic rocks cut by dikes, sills and irregular intrusions of porphyritic dacite and rhyodacite. Late mafic dikes and at least one dioritic to gabbroic intrusive intrude the felsic sequence. Figure 4 shows the bedrock geology of the immediate deposit area.

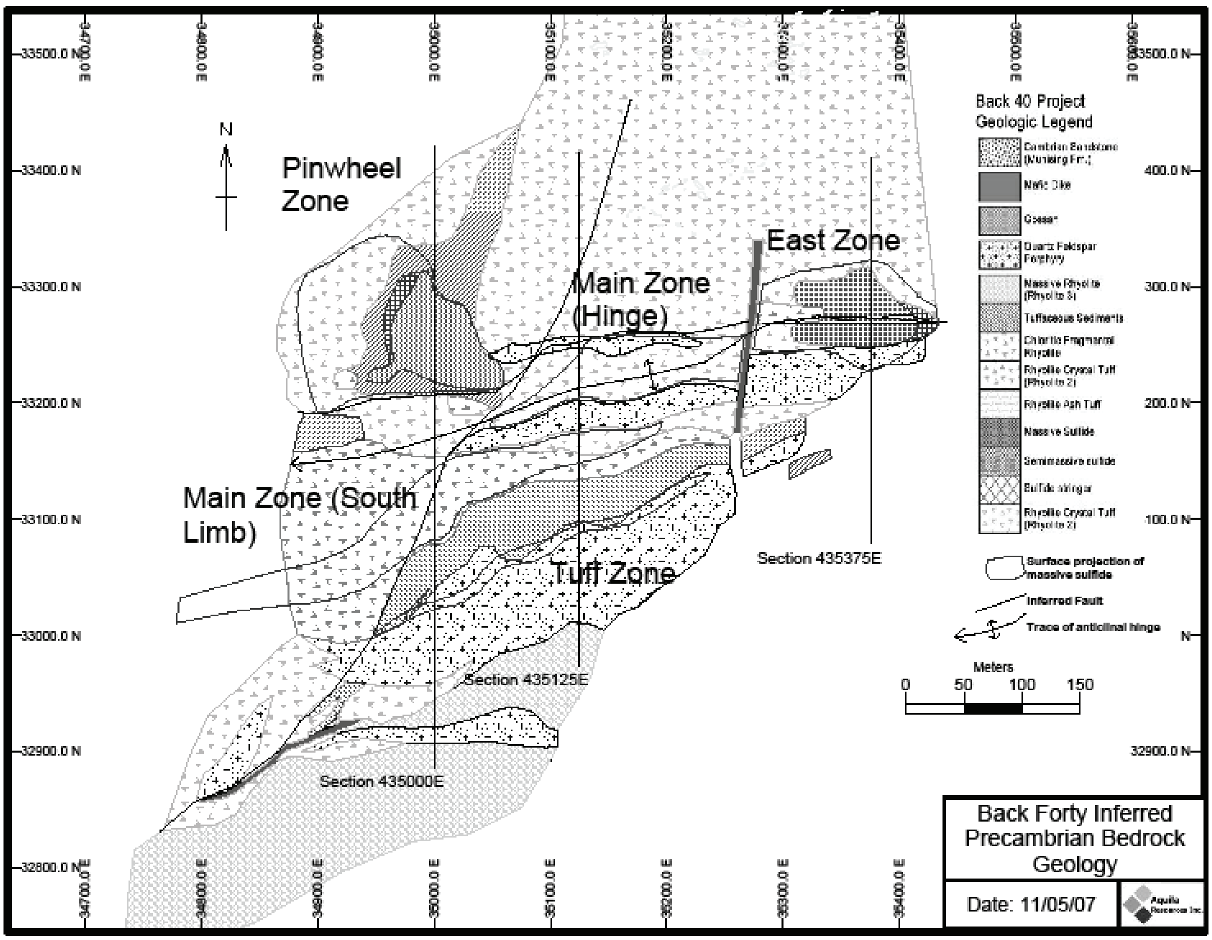


Figure 4 . Bedrock geology of the Back Forty deposit.

Rhyolitic rocks comprise the main host for the massive sulfide mineralization and consist of three chemically distinct sequences of rhyolite breccias, pyroclastic rocks and thin interbedded tuffaceous rocks. A well developed sequence of finely bedded tuffaceous sediments, including a cherty exhalative horizon, occurs at the break between the middle and upper rhyolite sequences. Younger dacitic quartz, feldspar porphyries intrude the entire sequence including the massive sulfides.

Structurally, this rhyolite sequence and associated massive sulfide mineralization has been deformed into an asymmetric, moderately plunging (30^0 west-southwest) anticlinal fold characterized by a gently dipping north limb (30^o northwest), a steeply dipping and sheared south limb (70^o southeast). The hinge of the fold and associated massive sulfide mineralization have been breached by erosion in the vicinity of the East Zone or near or at the fold's subcrop to the east. Folding has produced an axial planar schistosity and faulting has offset lithologies and created zones of weakness for younger intrusive rocks.

Three chemically distinct (but not always visually distinct) rhyolite sequences have been identified in the immediate area of mineralization. The units are identified as Rhyolite 1, 2 and 3 from oldest to youngest, as illustrated in the generalized stratigraphic column shown in figure 5.

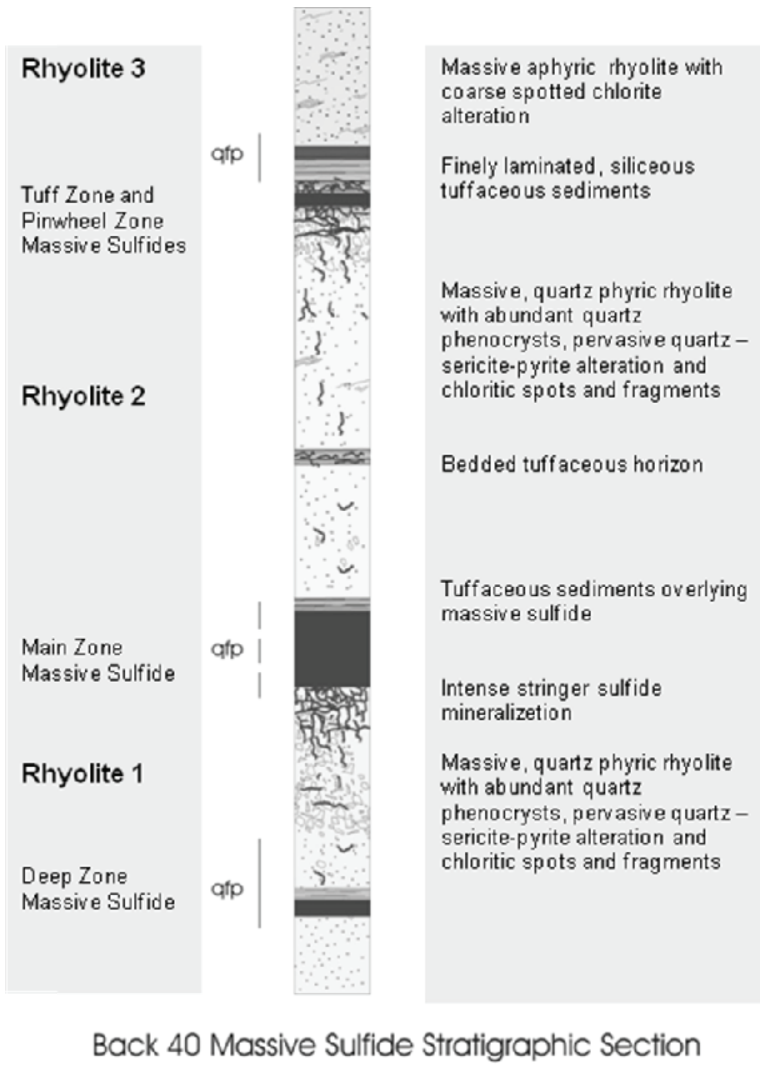


Figure 5. Rhyolite stratigraphic section with major massive sulfide zones.

Figure 6 shows two discrimination plots used to characterize Back Forty host rocks. The largely rhyolitic composition of the volcanic rocks is illustrated in the SiO_2 vs Zr/TiO_2 plot, and the immobile element plot of Zr/TiO_2 vs Al_2O_3/TiO_2 clearly distinguishes the three rhyolites.

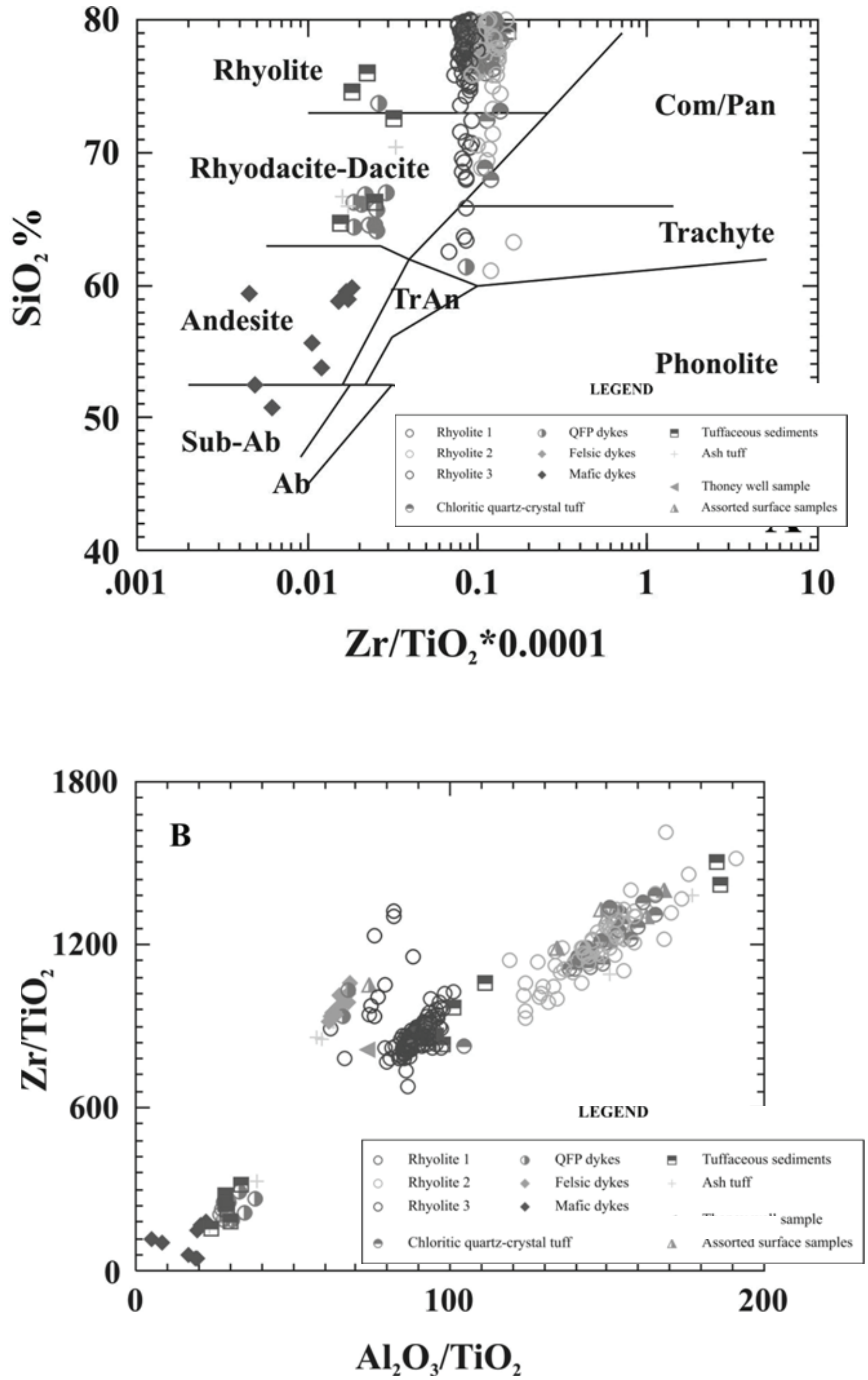


Figure 6. Discrimination diagrams for Back Forty host rocks.

All three rhyolite types exhibit intense leaching of Na_2O (feldspar breakdown) and concomitant increase in K_2O (sericitization) as a result of intense hydrothermal alteration. Altered host rocks form assemblages of quartz – sericite – pyrite throughout the drilled section hosting the massive sulfide mineralization and throughout an extensive area surrounding the known mineralization. The degree and extent of this alteration is evidence for a large and long lived hydrothermal system and suggests the potential for additional mineralization in the area.

Mineralization

Mineralization at the Back Forty project consists of base metal massive sulfide, semi massive sulfide and stringer sulfide mineralization as well as precious metal (gold and silver) mineralization.

Base metal mineralization

Massive, semi massive, and associated stringer sulfide mineralization occurs in at least 3 stratigraphic intervals roughly 100 m apart within the altered rhyolite sequence (figure 5), originally occupying horizons separating the major rhyolite eruptive events. Subsequent folding, shearing, faulting and emplacement of younger intrusive rocks has complicated and disrupted this primary stratigraphy.

Massive sulfides are dominantly of the zinc-rich variety although copper-rich zones occur in some lenses and copper-rich stringer mineralization is locally common. The felsic-dominant volcanic stratigraphy that is host to the Back Forty mineralization point to a bimodal-felsic or a Kuroko-style of mineralization, defined by having >50% felsic volcanic rocks, and <15% siliciclastic rocks in the host stratigraphic succession (Barrie, 2007).

Zinc-rich massive sulfides at Back Forty consist of medium to coarse grained aggregates of pyrite, sphalerite, and lesser chalcopyrite and galena, with varying amounts of silver and gold. Pyrite is the dominant gangue mineral with minor amounts of pyrrhotite and aresenopyrite. Galena attains potentially recoverable amounts in one of the zinc-rich massive sulfides (the Tuff Zone), which also contains elevated silver values relative to the other horizons.

Two massive sulfide lenses come to surface and have been intensely oxidized to form iron oxide-rich gossans which cap fresh massive sulfide. The gossan mineralization consists principally of botryoidal, colliform and brecciated hematite and goethite, with lesser amounts of the minerals found in the primary massive sulfide that have undergone partial to near complete replacement by the oxides. Minor to trace amounts of bornite, gold, argentite, diaphorite, acanthite, ramdohrite ($Ag_3Pb_6Sb_{11}S_{24}$), Ni-skutterudite, eugenite, meneghinite, clausthalite (PbSe), cassiterite, and other trace phases are present (Barrie, 2007). Gold and electrum are present at grain boundaries of other minerals, and within colloidal hematite. Although recoverable amounts of copper are present in the Pinwheel gossan, base metal tenors in gossan are generally very low, with gold and silver locally attaining very high grades.

Copper-rich massive sulfides are limited in extent relative to the zinc-rich variety, and are composed of mainly pyrite and chalcopyrite, with some supergene enrichment to bornite in near surface zones underlying gossan. Like the zinc-rich massive sulfides copper-rich zones contain varying amounts of gold and silver.

Textures in the massive sulfide lenses are massive to bedded with extremely variable bedding attitudes, indicating post depositional deformation and remobilization.

Stringer sulfide mineralization normally consists of cross cutting veins and fracture fillings of pyrite with varying amounts of chalcopyrite and gold, and normally underlies massive mineralization but may be laterally correlative with some massive lenses.

To better understand the geometry and stratigraphic position of the Back Forty massive sulfides, several views and cross sections are presented below. In plan view (Figure 4) the massive sulfide lenses occupy the hinge and north and south limbs of the folded stratigraphy. Figure 7 shows a longitudinal 3D section of the mineralized zones viewed from the north, and figures 8, 9, and 10 are cross sections (locations shown on figure 4) which further illustrate the morphology of the massive lenses and host rocks.

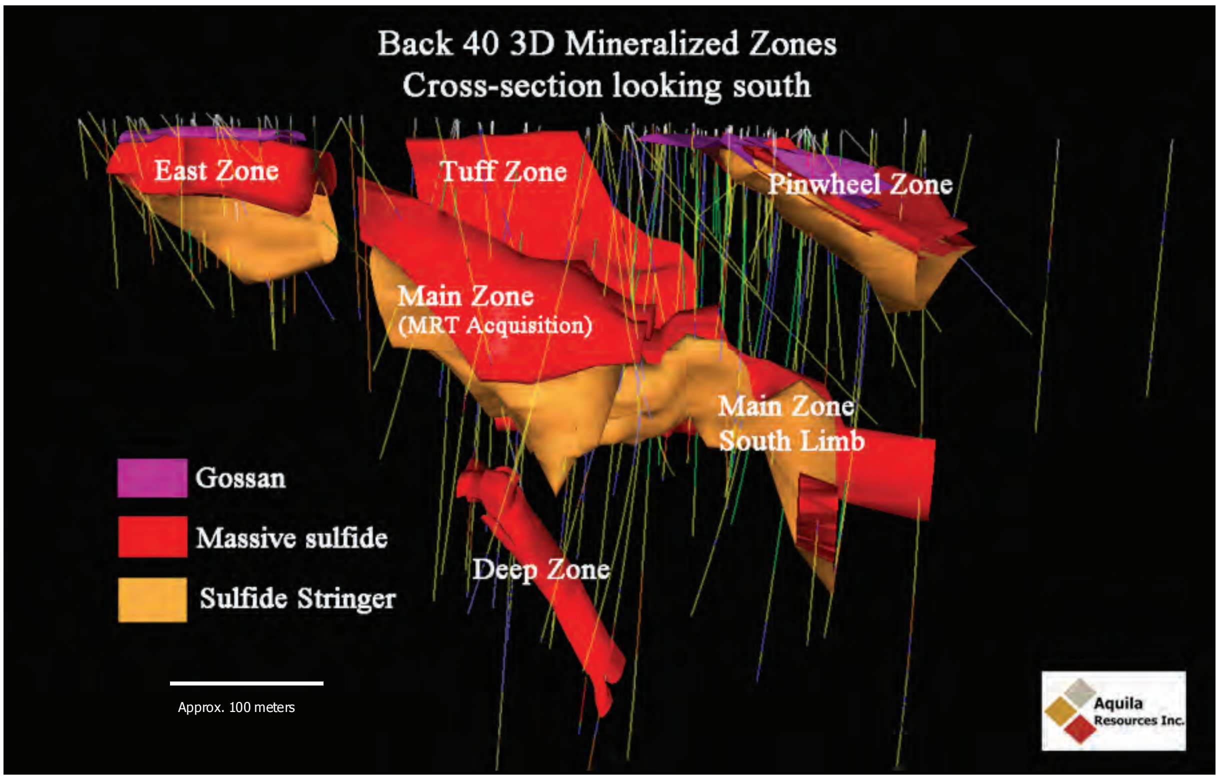


Figure 7. Three dimensional view of Back Forty sulfide and gossan mineralization.

Figure 8. Cross section of the near surface East Zone. For legend see figure 4. Scale is in meters.

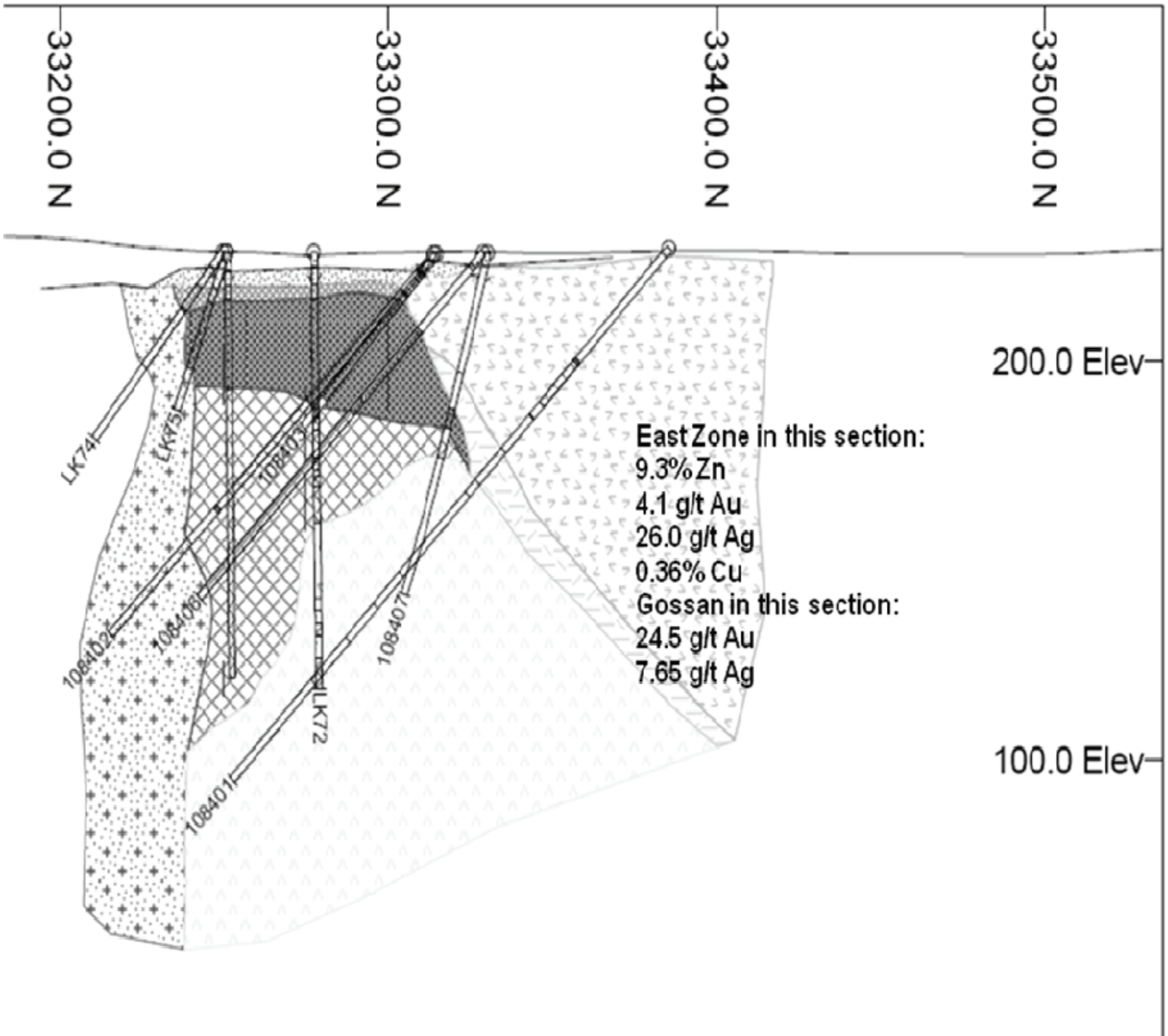


Figure 9. Cross section through the Main Zone (hinge area and south limb) and Tuff Zone. For legend see figure 4. Black diamonds represent gold intercepts.

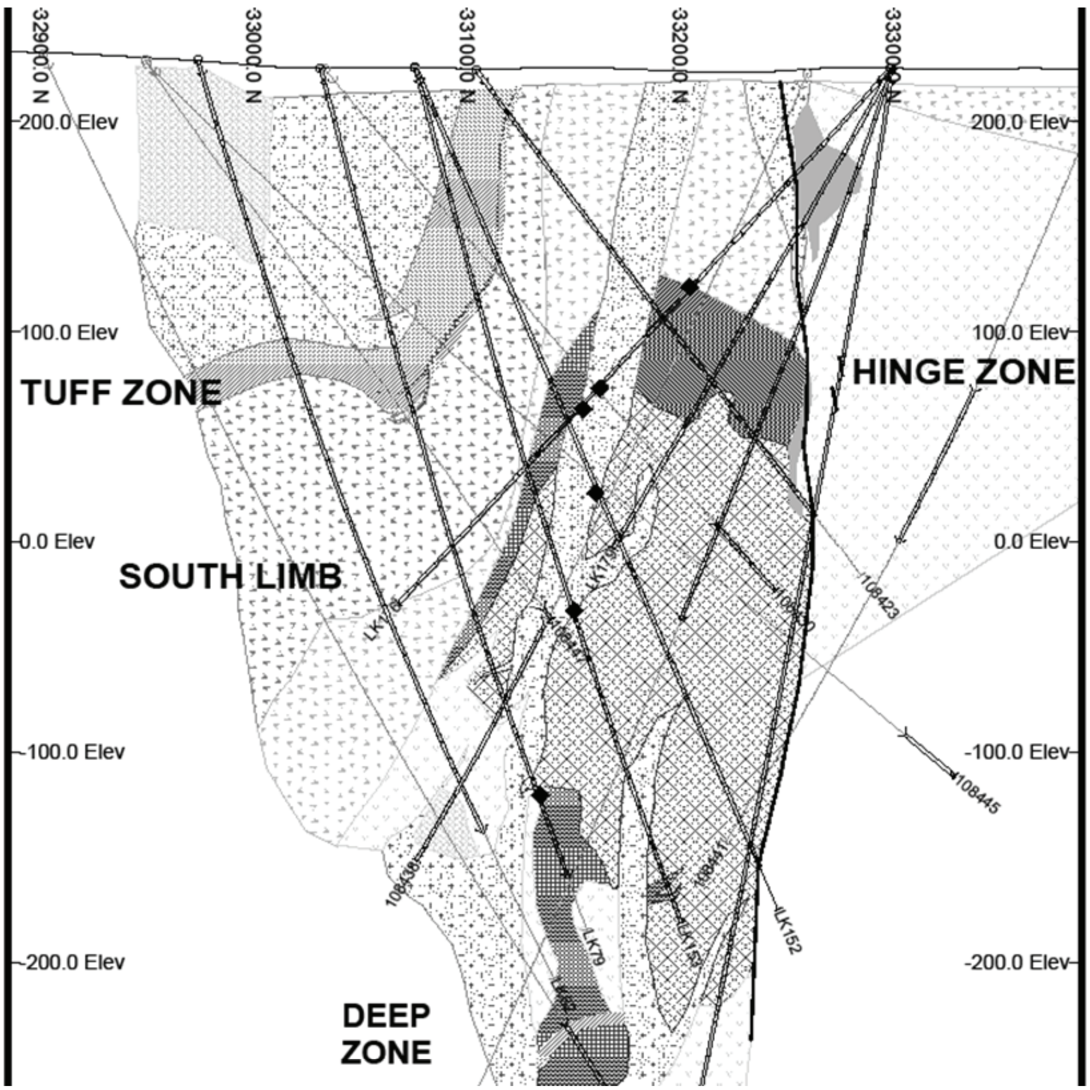
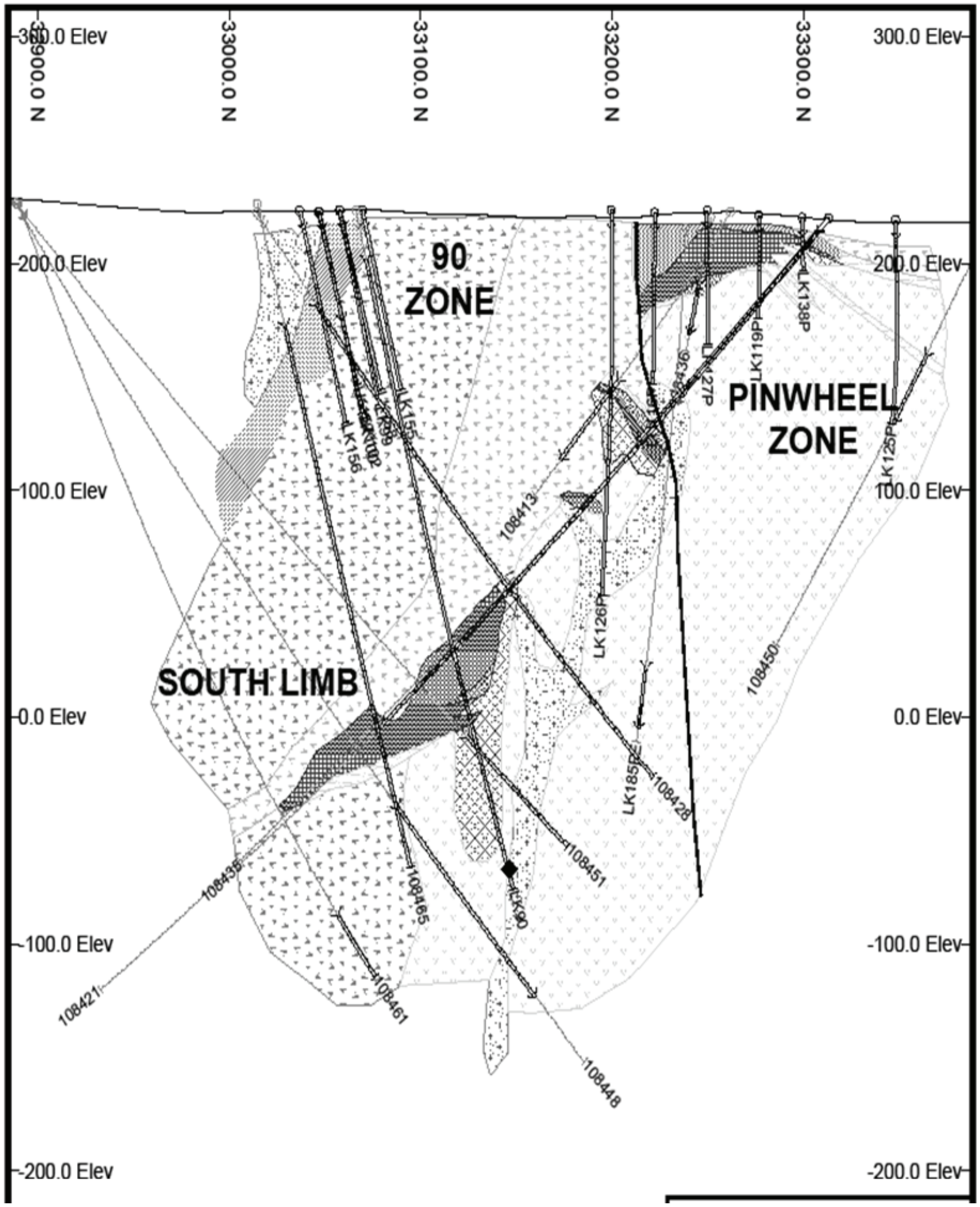


Figure 10. Cross section through the Pinwheel and 90 Gold Zone. For legend see figure 4.



Metal distribution is variable within massive sulfides and associated host rocks. Figures 11 and 12 illustrate the typical patterns of base and precious metals in massive sulfides, stringer zones, altered host rocks and younger intrusive porphyry.

Figure 11. Metal distribution, Main Zone (Hinge area) massive sulfide and stringer zone. This pattern of metal distribution is typical of the Main Zone with zinc grades increasing towards the bottom of the massive sulfide with strong and consistent gold mineralization in the underlying stringer sulfides. Note also the gold values associated with the intrusive quartz – feldspar - porphyry (QFP).

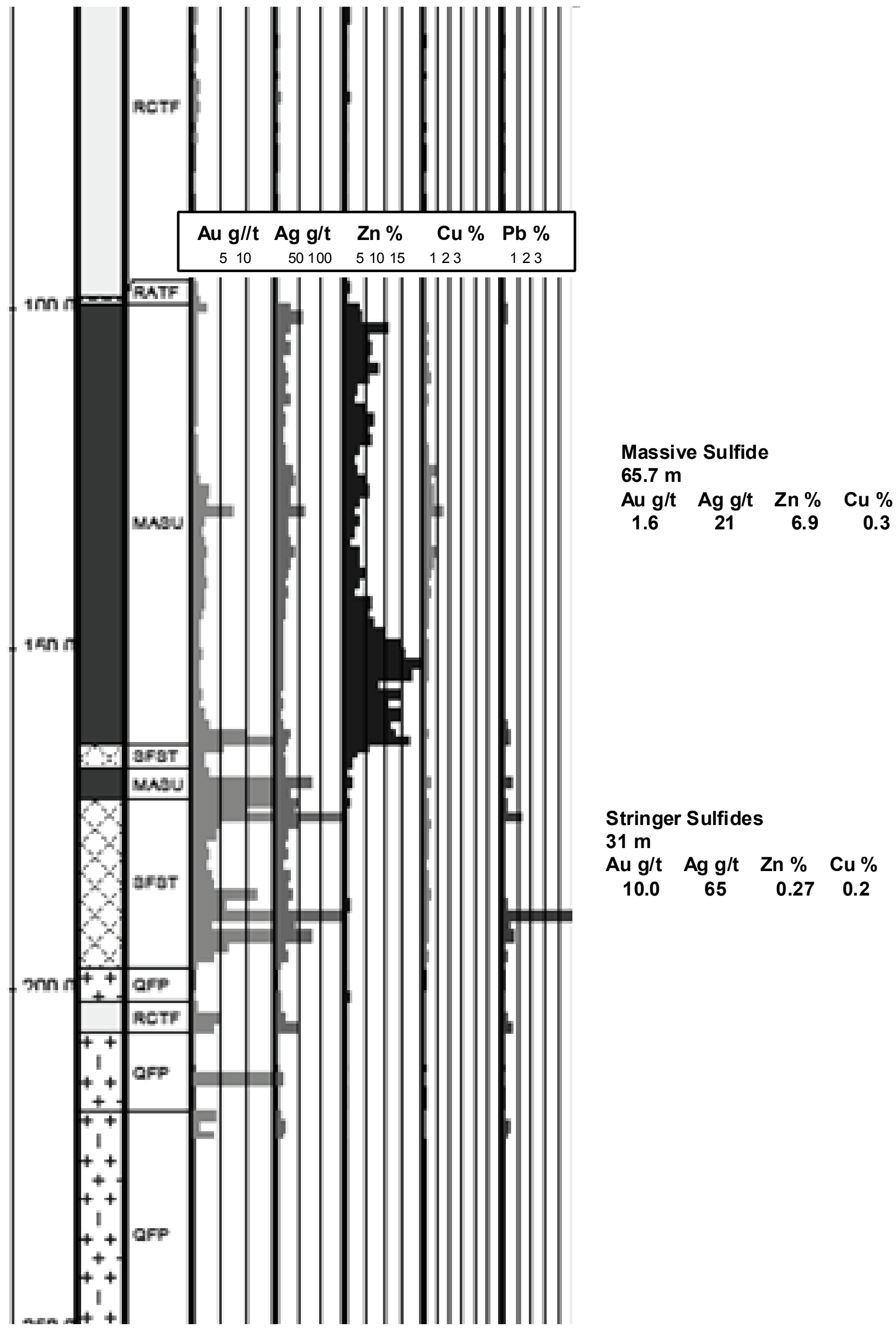
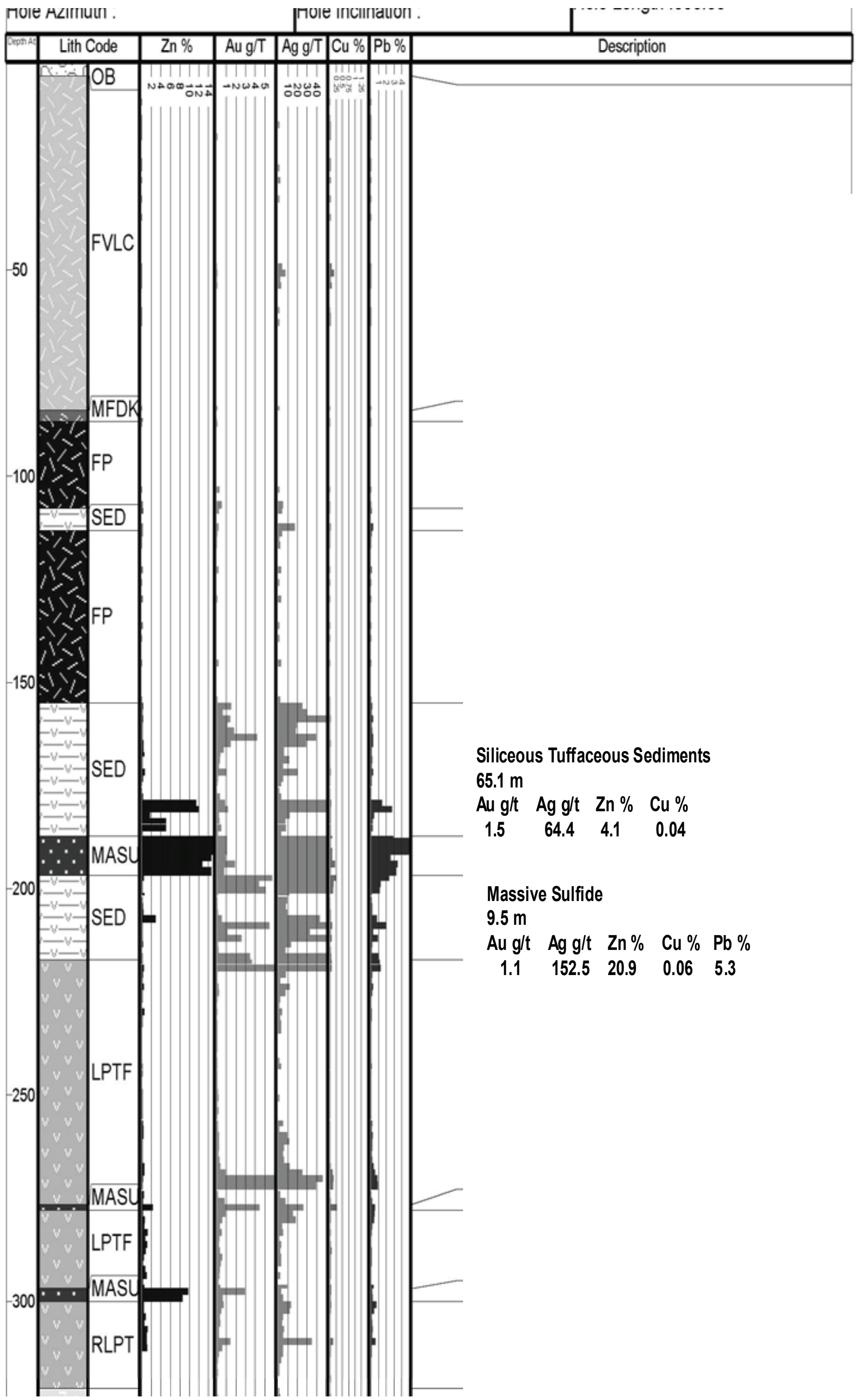


Figure 12. Metal distribution associated with Tuff Zone massive sulfide mineralization. Note the widespread gold and silver values in the tuffaceous sediment sequence hosting this massive sulfide lens.



Precious metal mineralization at Back Forty

Gold and silver occurs in all types of sulfide mineralization (massive sulfides, stringer zones), as well as gossans, altered rhyolite host rocks, and younger intrusive porphyries which cut the host strigraphy and sulfide mineralization.

Gold in massive sulfides and associated stringer zones is of variable grade, and although it can attain very high grades locally (> 20 g/t), the average for all massive sulfides is 2.3 g/t. A breakdown of metal grades by individual sulfide zone is shown in figure 13. Gold in sulfide mineralization is usually fine grained and is closely associated with chalcopyrite and as native gold and electrum within pyrite and along pyrite grain boundaries.

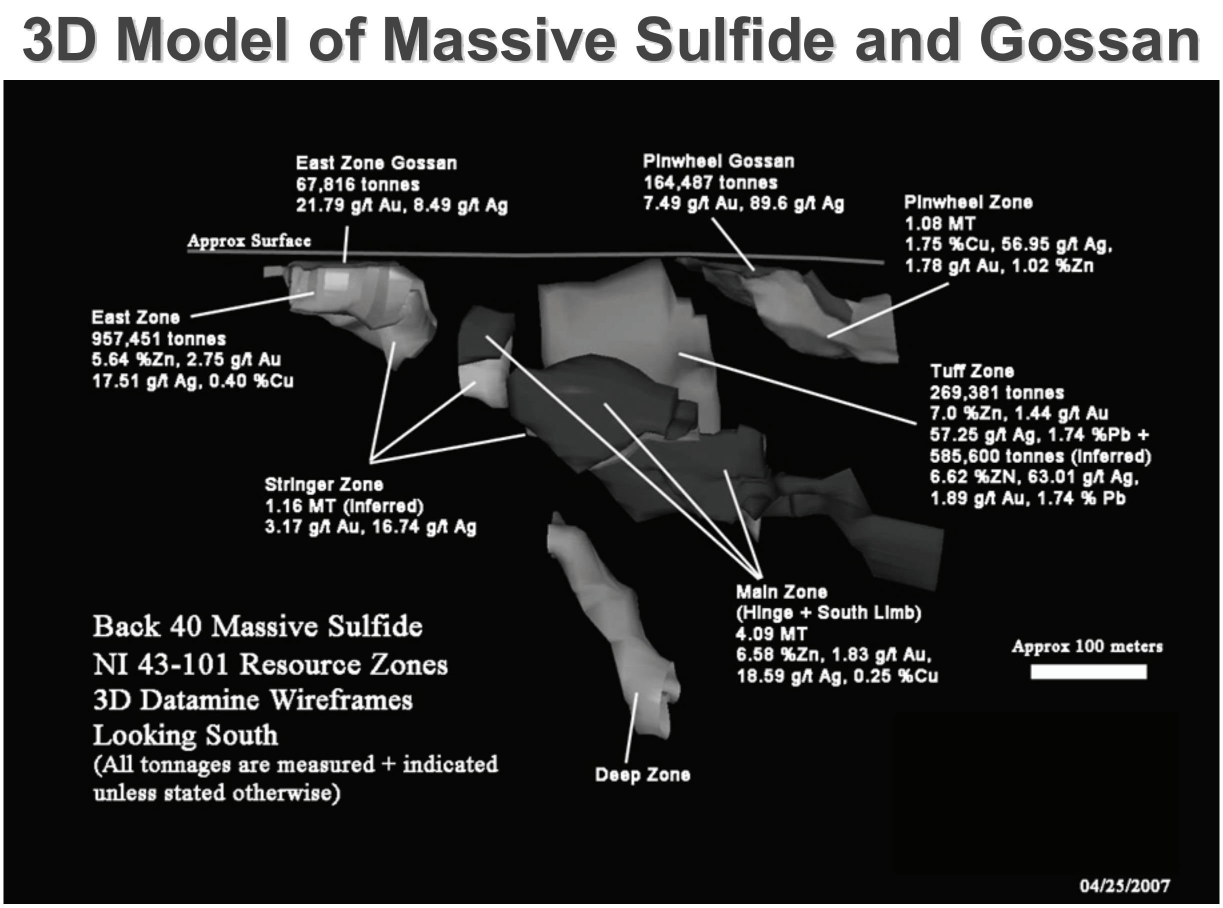
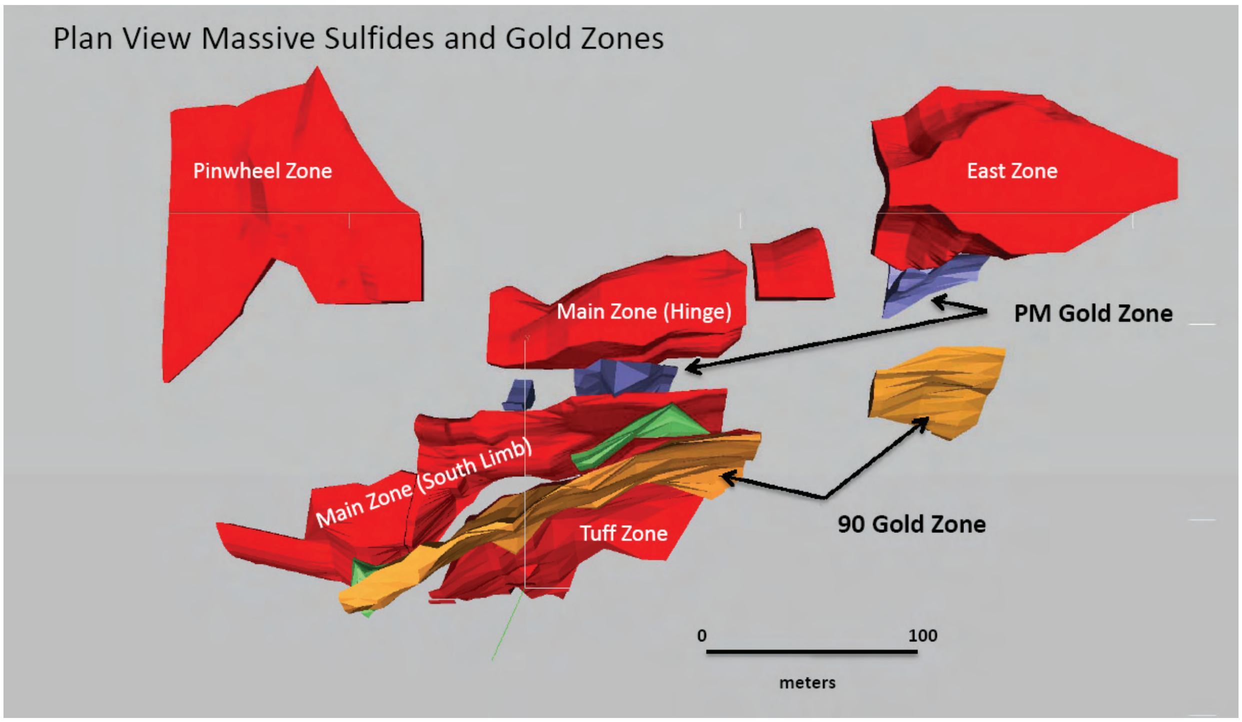


Figure 13. Tonnage and grade for individual sulfide zones (April 2007 NI-43-101 Resource)

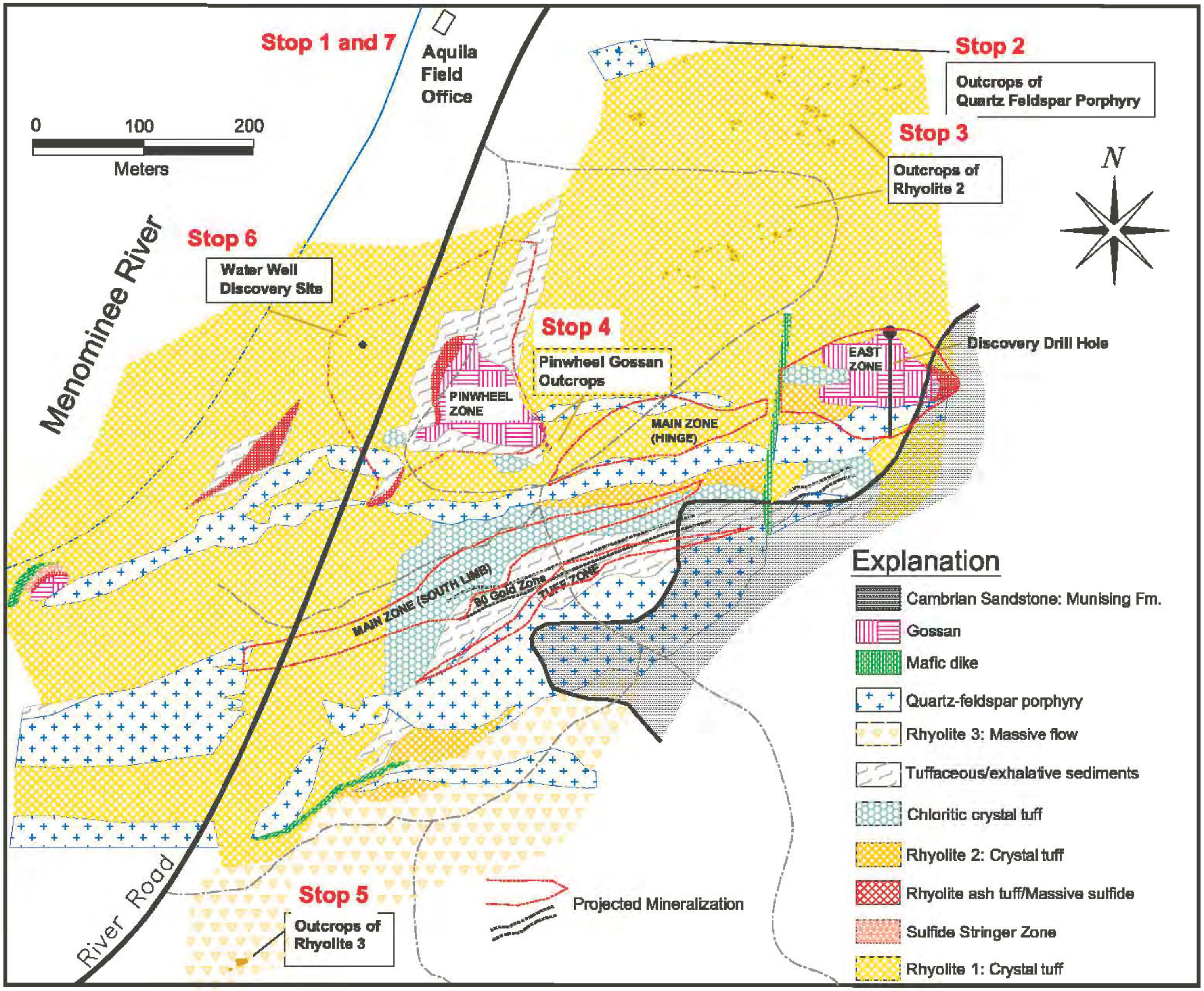
Gossan mineralization derived from the oxidation of massive sulfide shows strong enrichment in gold overlying the East Zone and gold and silver overlying the Pinwheel, as illustrated by the resource numbers in Figure 13. Fine grained, free gold in hematite is common in the gossan. Silver occurs in mercury silver minerals, eugenite ($Ag_{11}Hg_2$) and luanheite (Ag_3Hg), and in acanthite (AgS), and locally as coarse native silver.

Not shown in figure 13 is precious metal mineralization associated with rocks surrounding massive sulfide mineralization. Numerous gold and silver intercepts in lithologies peripheral to the massive sulfides and stringers prompted follow up drilling in 2007 and 2008 to target this style of mineralization. As a result of this drilling, two zones of gold and silver mineralization – the 90 Gold Zone hosted by siliceous sediments, and the PM Gold Zone hosted by quartz feldspar porphyry have been identified (figure 14). Both gold zones contain fine grained gold disseminated in silicified host rock with small amounts of galena, aresenopyrite, chalcopyrite and pyrite.

Figure 14. Plan view of massive sulfide lenses and gold zones



Expansion of all mineralized zones is ongoing at the project with 3 drills active. A new resource estimate is currently being prepared and preliminary mine planning, metallurgical studies, and environmental baseline work is underway.


Stop 1 and 7
Aquila
Field
Office
0
100
200
Meters
Menominee River
Stop 6
Water Well
Discovery Site
Stop 4
Pinwheel Gossan
Outcrops
PINWHEEL
ZONE
MAIN ZONE
(HINGE)
MAIN ZONE (SOUTH LIMB)
90 Gold Zone
TUFF ZONE
EAST
ZONE
Discovery Drill Hole
Stop 2
Outcrops of
Quartz Feldspar Porphyry
Stop 3
Outcrops of
Rhyolite 2
N
Stop 5
Outcrops of
Rhyolite 3
River Road
Projected Mineralization
Explanation
Cambrian Sandstone: Munising Fm.
Gossan
Mafic dike
Quartz-feldspar porphyry
Rhyolite 3: Massive flow
Tuffaceous/exhalative sediments
Chloritic crystal tuff
Rhyolite 2: Crystal tuff
Rhyolite ash tuff/Massive sulfide
Sulfide Stringer Zone
Rhyolite 1: Crystal tuff

FIELD TRIP DESCRIPTION AND STOPS

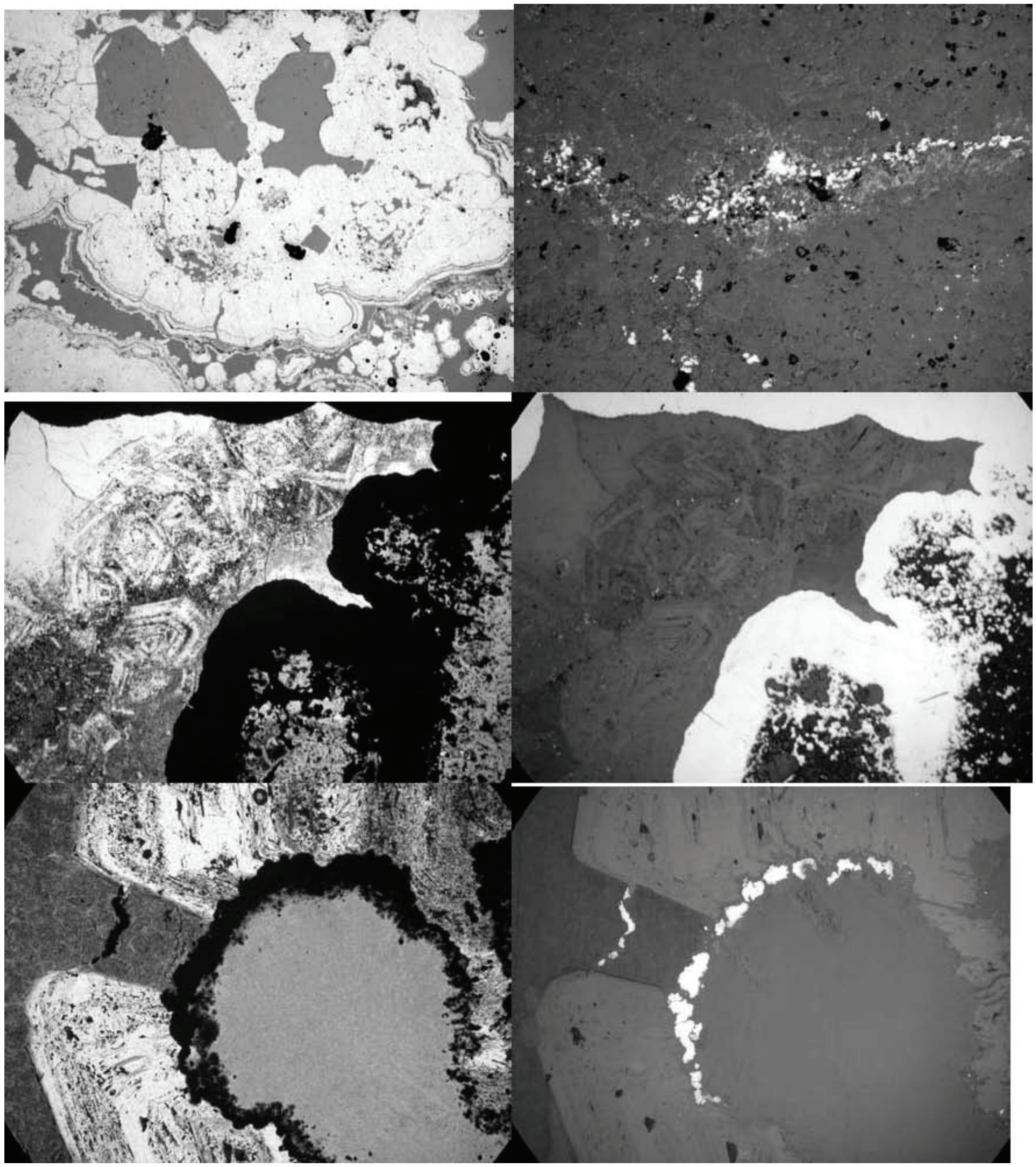
The field trip will concentrate on local and deposit geology to be illustrated by inspection of outcrops in the vicinity of the Back Forty mineralization, drill core, and a review of technical data developed from geophysical studies and drilling.

Stop 1 Field Office: The Aquila field office is located directly adjacent to the Back Forty massive sulfide discovery. Field trip participants will assemble at the field office for an overview of the project setting.

Stop 2 Porphyry Outcrops: From the field office, proceed across the River Road to outcrops of quartz-feldspar porphyry. These outcrops are a couple of hundred meters north of the main mineralization but are typical of this rock type which occurs as dikes, sills and irregular intrusions throughout the host rhyolite sequence. Compositionally they are dacitic to rhyodacitic and typically fine to medium grained with a dark ground mass of chlorite, biotite, amphibole, sericite and 5mm to 1 cm phenocrysts of feldspar and lesser quartz. These units are variably altered and locally gold mineralized – especially along margins where they intrude rhyolite with heavy or massive sulfide. Where they are mineralized they are normally silicified with destruction of phenocrysts, and contain minor amounts of chalcopyrite, sphalerite, galena and aresenopyrite and occasionally visible gold.

Stop 3 Rhyolite 2 Outcrops: Abundant outcrops of altered rhyolite occur in a broad area north of the known massive sulfide mineralization, and are likely hanging wall (Rhyolite 2) to the Main Zone (Hinge, South Limb and East Zone) massive sulfides, occurring on the northwest dipping, north limb of the west south west plunging, asymmetric fold. These outcrops contain quartz phenocrysts in a fine matrix of sericite and quartz which is typical of Rhyolites 1 and 2, and are considered to be favorable host rocks for massive sulfide mineralization. They contain abundant disseminated pyrite and only rarely sphalerite or other base metal sulfides and are considered part of the large hydrothermally altered halo to the massive sulfide system. The only obvious texture is a steeply dipping planar fabric – probably an axially planar cleavage related to the fold system.

Stop 4 Pinwheel Gossan: Gossan outcrops here are the only exposure of massive sulfide (formerly) at the project, and are completely to partially oxidized rocks composed principally of botryoidal, colliform and brecciated hematite and goethite, clays, and chlorite, with lesser amounts of the minerals found in the primary massive sulfide that have undergone partial to near complete replacement by the oxides. Minor to trace amounts of bornite, gold, argentite, diaphorite, acanthite, ramdohrite ($Ag_3Pb_6Sb_{11}S_{24}$), Ni-skutterudite, eugenite, meneghinite, clausthalite (PbSe), cassiterite, and other trace phases are present. Gold and electrum are present at grain boundaries of other minerals, and within colloidal hematite. These outcrops represent the up dip extension of the Pinwheel massive sulfide, near the axis of the fold, where the Pinwheel Zone has been breached by erosion. The Pinwheel represents a stratigraphically higher sulfide horizon than the Main Zone massive sulfides which are located about 100 meters below the outcrops of gossan. This area of the Pinwheel gossan contains significant magnetite and the resulting ground magnetic response clearly defines this portion of the gossan. Other parts of this gossan as well as the entire East Zone gossan however, are totally non magnetic.



Reflected light (RL) and transmitted light (TL) photomicrographs of *gossan samples.* **Top left:** East zone gossan: LK-76 10.1-10.85 - gold in colloidal hematite;

0.8 mm; RL. **Top right:** top of 90 zone: LK-99 32.-33.5 - tiny gold-electrum granules with pyrrhotite, galena (grey) and acicular ramdohrite (grey) in vein in hematite matrix. 1.3 mm; RL. **Middle left and right:** Pinwheel gossan: LK-130P 10.2-11.08 -zoned dolomite filling void between colloidal cpy rimming UM9. 5.8 mm, TL (left) and RL (right). **Bottom left and right:** Pinwheel gossan: LK-130P 14-15.3: -mercury-silver aggregates rimming an unidentified mineral and against zoned carbonate. 1.5 mm TL (left) and RL (right). From Barrie (2007).

Stop 5 Rhyolite 3 Outcrops: Outcrops of rhyolite 3 are exposed south of the fold axis on the south limb of the fold. Unlike rhyolites 1 and 2, Rhyolite 3 is a non porphyritic rhyolite (usually) and chemically distinct from the other rhyolites. This unit is also highly altered – sericite, chlorite, silica, and pyrite, and in drill core contains very distinctive round or ovoid, dark chloritic alteration spots. It also contains appreciable pyrrhotite and has a resulting positive magnetic signature. The stratigraphic position of this unit, although shown as the stratigraphically highest rhyolite (figure 5), is actually uncertain. It has not been identified on the north limb of the fold, and may represent a younger intrusive unit into the mineralized rhyolite sequence.

Stop 6 Water Well Location: This is the site of the original water well which encountered massive sulfides. The well was drilled by Kleiman Pump and Well from Iron Mountain Michigan. The drillers recognized heavy sulfides in the cuttings and subsequently contacted geologist Richard Lassin who analyzed them and confirmed high (10%) zinc values. Lassin and Kleiman also identified the gossan outcrops and correctly speculated that the water well intercept represented the down dip, unoxidized Pinwheel massive sulfide. After contacting and partnering with Minerals Processing Corp. – a privately held Michigan exploration company – a gravity survey was conducted down the River Rd. between the gossan outcrops and water well, as well as on State of Michigan owned minerals to the east. Both surveys detected strong gravity responses. A coincident electromagnetic response on the state ground, prompted the initial diamond drilling program. This is the site of the discovery hole, in what is now the East Zone massive sulfide.

Stop 7 Field Office: Drill core of representative mineralization and host rocks and other technical information will be on display.

Stop 8 Daggett Core Facility: More core will be on display with assay and other information at the core storage facility in Daggett Michigan.

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54th Annual Institute on Lake Superior Geology

Field Trips 4 and 8

GEOLOGY OF THE EAGLE PROJECT

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Proterozoic high-MgO basaltic magmatism in the Midcontinent Rift system, northern Michigan: Precise baddeleyite U-Pb age and petrogenesis of the Eagle sulfide-bearing mafic-ultramafic intrusion

Introduction

The Eagle sulfide-bearing intrusion, first drilled in 2001 by Kennecott Mineral Company, consists of both disseminated and massive sulfides in most parts of the intrusion. The Eagle intrusion is part of the intrusive-extrusive association in the 1100 Ma Midcontinent Rift System (MRS). Major exposures of the volcanic rocks occur along the shores of Lake Superior, but not in the Eagle area. Instead, equivalent mafic dikes are abundant in the Eagle area. The styles of sulfide mineralization in the Eagle intrusion differ significantly from those associated with Duluth and Mellen Complex, the principle exposed plutonic rocks of the rift. In the Duluth Complex sulfide mineralization is restricted to the basal contact zones whereas Eagle sulfide mineralization is distributed throughout the host intrusion. The Cu, Ni, and PGE tenor of the sulfide ores from Eagle are also much higher. These features, together with higher olivine abundance and a lack of layering in the Eagle intrusion suggest that the Eagle intrusion may represent a dynamic magma conduit similar to the feeder dyke of the Voisey's Bay Ni-Cu sulfide deposit in Labrador. The summary below represents our current understanding of the Eagle system based on the preliminary results of a collaborative study with Kennecott Minerals Company.

Geological backgroud

The Eagle Ni-Cu sulfide deposit occurs in the Baraga basin in northern Michigan (Fig.1). The Baraga basin was intruded by the Mesoproterozoic Baraga-Marquette dike swarm, which is considered to be related to the early stage basaltic magmatism in the MRS (Wilband and Wasuwanich, 1981, Green et al., 1987). Sulfide mineralization occurs in two intrusions referred to as the Eagle and East Eagle deposits. The western intrusion, which hosts the Eagle deposit, is ~480 m in length and 100 m wide near the surface. It narrows to ~10 m at the depth of ~340 m. The eastern intrusion is located 650 m to the east of the Eagle deposit.

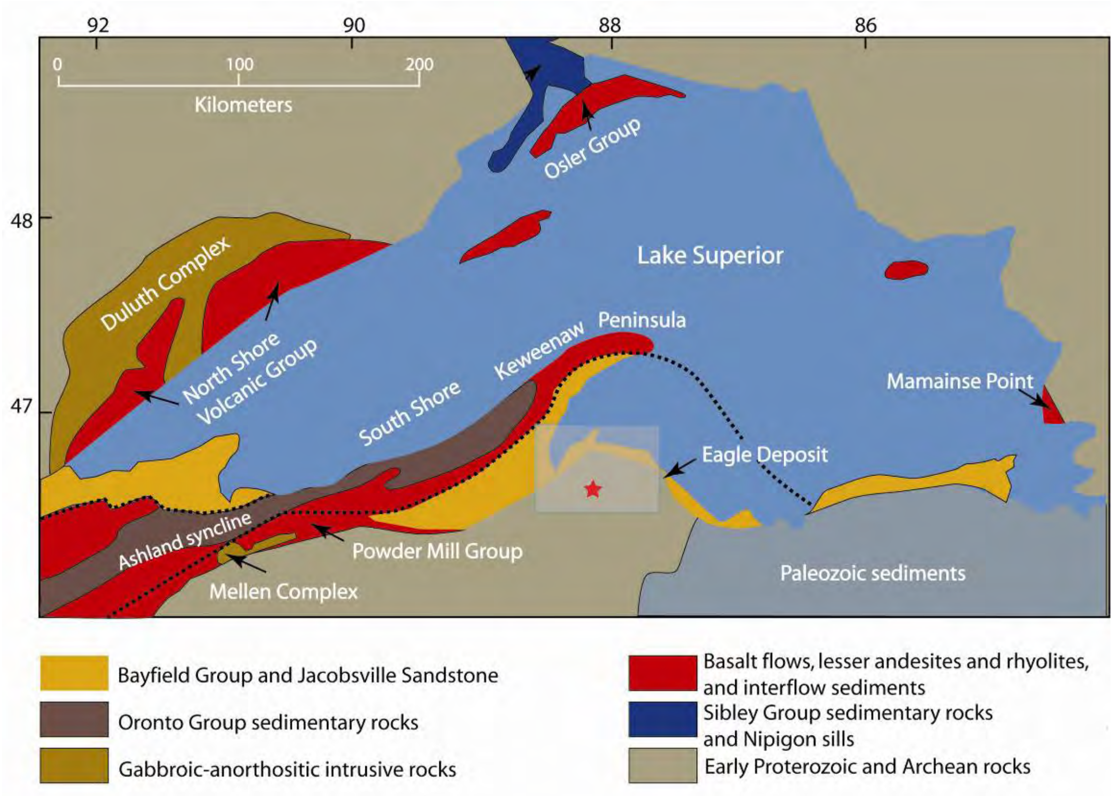

Fig.1 Map of the Lake Superior region showing major exposure of volcanic and plutonic rocks associated with the Midcontinent rift (after Davis and Green, 1997; Nicholson et al., 1997).

The exposed volcanic rocks of the MRS are located around Lake Superior in southern Ontario, northern Minnesota, northern Wisconsin and Michigan. Volcanic rocks are also found in deep drill cores as far south as Kansas. Most of the volcanic rocks are thoeliitic in nature, with smaller amounts of intermediate and rhyolitic rocks (e.g. Nicholson et al., 1997).

The principal intrusive rocks of the MRS are the Duluth Complex in Minnesota and the Mellen Complex in Wisconsin, both of which contain low-grade Ni-Cu sulfide mineralization. The Duluth Complex and associated subvolcanic intrusions comprise a large (5,000 km^2) intrusive complex that represents a significant low-grade, but high tonnage, resource. The smaller Mellen Complex emplaced near the base of the Keweenawan volcanic section along the southeastern flank of Lake Superior, also contains low-grade mineralization. U-Pb dating of zircons from various intrusions in the Duluth Complex provides an age of 1099 Ma (Paces and Miller, 1993) and correlates with Keweenawan high Al olivine tholeiite basalts of the North Shore volcanic group (Chalokwu et al., 1996). The Mellen Complex was emplaced at 1102 Ma, and has been correlated with the Kallander Creek Volcanics of the Powder Mill group (Zartman et al., 1997).

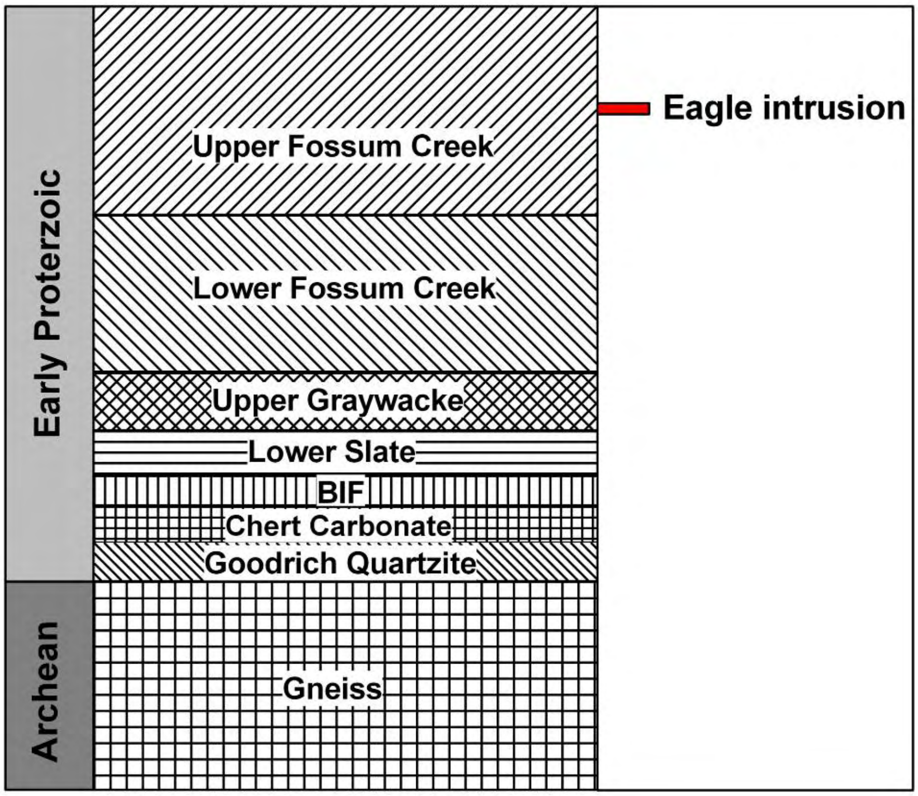

Fig.2 Stratigraphic diagram illustrates country rock around Eagle deposit, including Arhcean gneiss and Proterozoic sediment.

The Eagle intrusion intruded Early Proterozoic sedimentary rocks of the Marquette Range Supergroup in the Baraga Basin (Fig.2). The Marquette Range Supergroup is divided into the Chocolay, Menominee, and Baraga Groups. The Baraga Group is thought to be contemporaneous with the Proterozoic Animikie Group in Minnesota (Ojakangas et al., 2001). In the Baraga Basin, the Baraga Group sediments are low-grade metamorphosed marine sediments that contain disseminated pyrite, pyrrhotite, or both. The Baraga basin is bounded to the north and south by Late Archean gneiss and granitoids, and to the east and southeast by Late Archean, low-grade metamorphosed volcanic and sedimentary rocks. The lowest member of the Baraga Group is the Goodrich Quartzite, which is overlain by a chert carbonate member. The chert carbonate member is overlain by the Michigamme Formation. Kennecott geologists informally divide the Michigamme Formation into three members: the Lower Slate, Upper Greywacke, and Fossum Creek. Sulfide and graphite-rich horizons are present in the Lower Slate and Lower Fossum Creek units. The sulfide assemblages are pyrrhotite-dominant, with lesser amounts of pyrite, chalcopyrite, and pentlandite.

Lithology and sulfide mineralization of the Eagle intrusion

The Eagle intrusion comprises feldspathic peridotite, gabbronorite, melatroctolite, melagabbro and olivine gabbro (Fig.3 and Fig.4). The basal contact occurs as an elongated feeder, which is composed of melatroctolite, which ranges in dip from steeply southeast to vertical. The melatroctolite is not restricted to the basal contact of the steeply dipping feeder, but can occur higher where it turns into a flat lying sheet. The melatroctolite is also discontinuously underlain by a thin (~25 m thick) olivine gabbro. In the central part of the Eagle intrusion, thick melatroctolite encloses ~60 m of melagabbro. However, there is no thermal contact or chilled margin between melatroctolite and melagabbro. In the upper part of the intrusion, the melagabbro is overlain by feldspathic peridotite. Gabbronorite occurs as enlongated lenses (a few meters thick), along the contact between feldspathic peridotite and melatrocolite. In general, lithological units of the Eagle intrusion show a broad range of orientations. Most strike east-southeast parallel to the trend of the Eagle intrusion and have flat to moderate dips to both north and south.

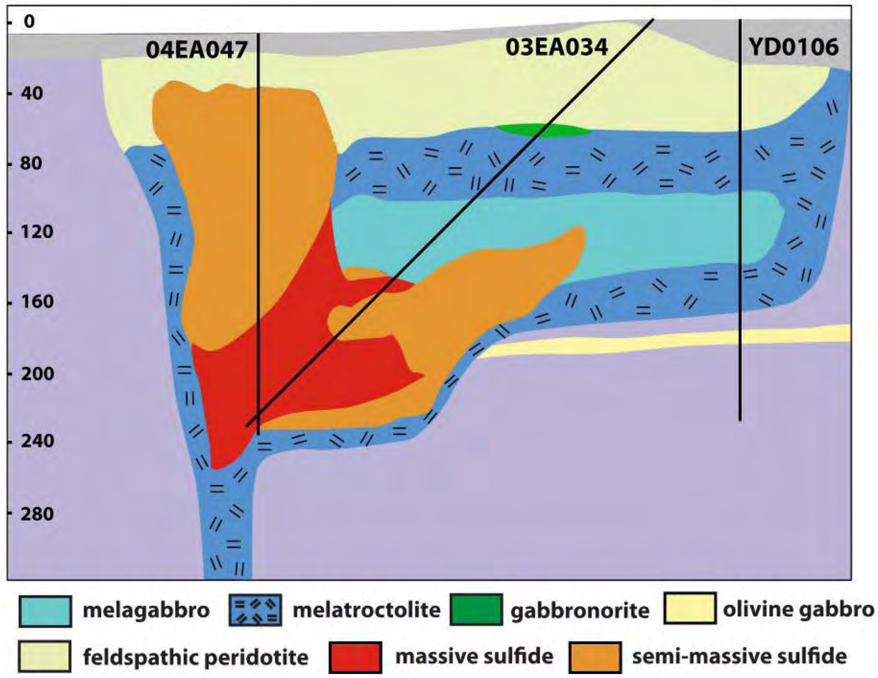

Fig.3 Long section through the Eagle intrusion showing its stratigraph

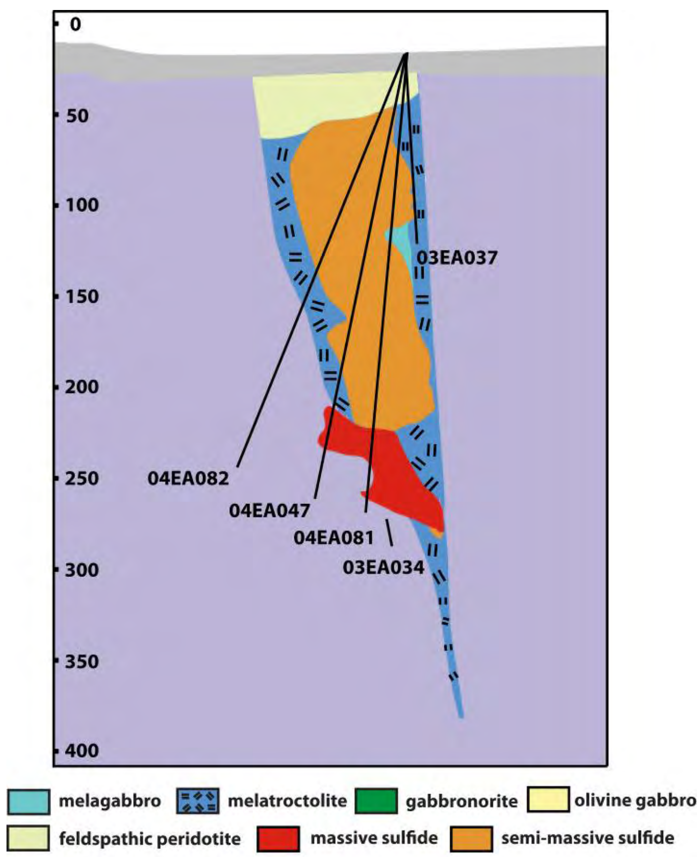

Fig.4 Section 431470E showing the stratigraphy of the Eagle intrusion

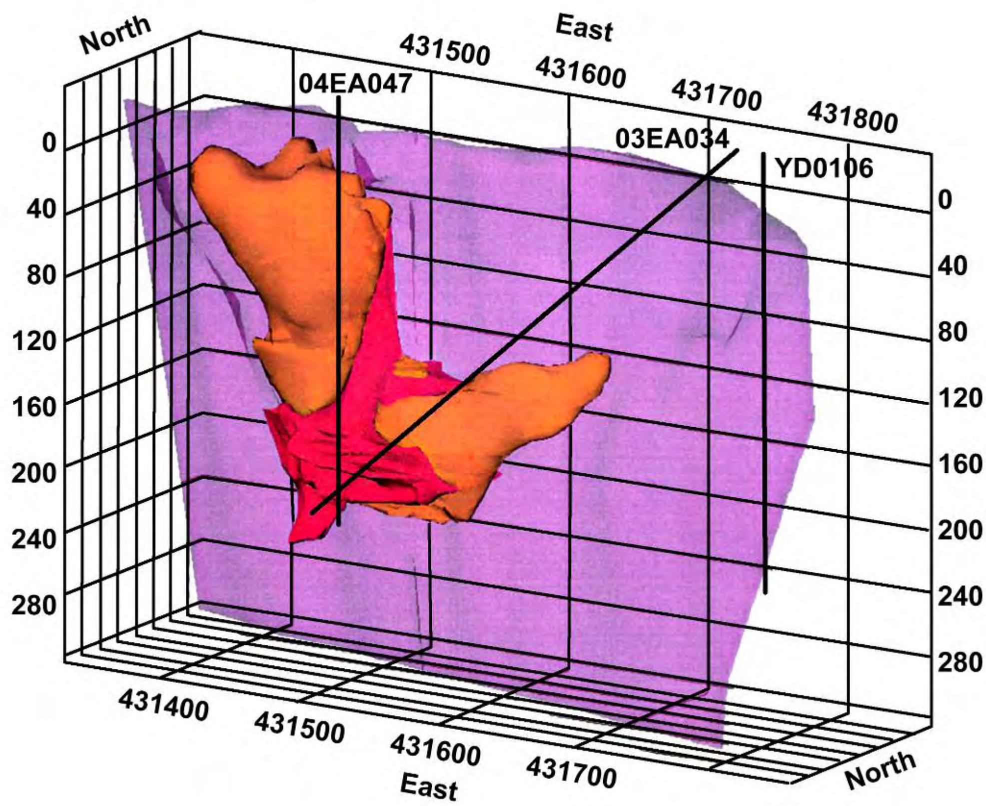

Fig.5 Block diagram illustrating ore body distribution

Three distinct types of sulfide mineralization occur at the Eagle deposit (Fig.5). They are described as disseminated, semi-massive and massive sulfide. Finely disseminated sulfide minerals can be found in most portions of the intrusion. The ore reserve is comprised of two semi-massive sulfide zones that are linked by a zone of massive sulfides. The mineralogy is typical of magmatic sulfides, and consists of pyrrhotite, chalcopyrite, pentlandite, and cubanite. The average grade of semi-massive sulfide ores are 2.1% Ni, 2.2% Cu, 0.5 g/t Pt and 0.3 g/t Pd. The average grade of massive sulfide ore is 6.1% Ni, 4.2% Cu, 1.1 g/t Pt and 0.8 g/t Pd.

Petrography

Modal proportions of minerals in rock samples from the Eagle intrusion have been estimated by point-counting. The results are shown in Fig.6. Olivine occurs as cumulus phases and pyroxene and plagioclase occur as interstitial phases in olivine-rich samples. But pyroxene and plagioclase occur as cumulus phases in olivine-poor or olivine-free samples. The percentage of granular, cumulus olivine grains increase from melagabbro, to melatroctolite, to feldspathic peridotite. Spinel occurs as inclusions in olivine suggesting that it is also an early cumulus phase. Minor amounts of amphibole and biotite occurs as interstitial phases in all samples.

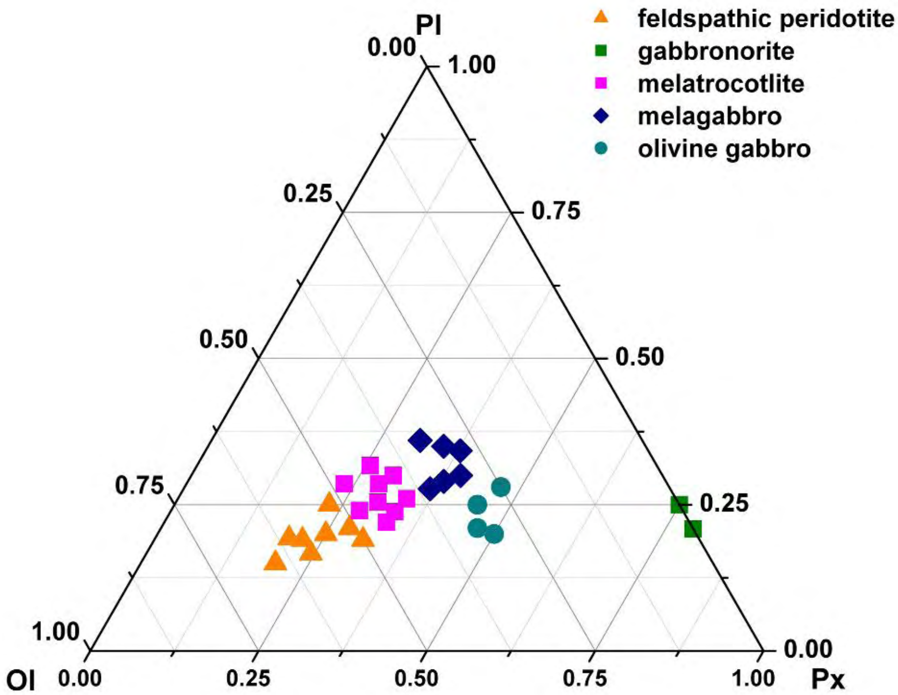

Fig.6 Modal proportions of the main rock types in Eagle intrusion plotted in Olivine-pyroxne-plagioclase phase diagram constructed after Morse (1980).

Feldspathic peridotite (Fig.7a) consists of 50-65% cumulus olivine (average grain size < 5 mm), forming as large crystals. Intercumulus pyroxene (20-30%) commonly forms okiocrysts (3-5 mm). Intercumulus plagioclase (15-25%) occurs typically as euhedral to subhedral grains of variable size. Spinel (< 2%) occurs as inclusions in olivine and poikilitic pyroxene and plagioclase.

Melatroctolite (Fig.7b) consists of 40-50% cumulus olivine (3~5 mm) occuring as medium to large elliptical grains, or as inclusions in pyroxene and plagioclase. Pyroxene (20-35%) occurs as euhedral to subhedral, intercumulus grains of variable size and plagioclase (20-30%) occurs as tabular, randomly oriented grains in the intercumulus space. Minor spinel inclusions are present in olivine, pyroxene and plagioclase.

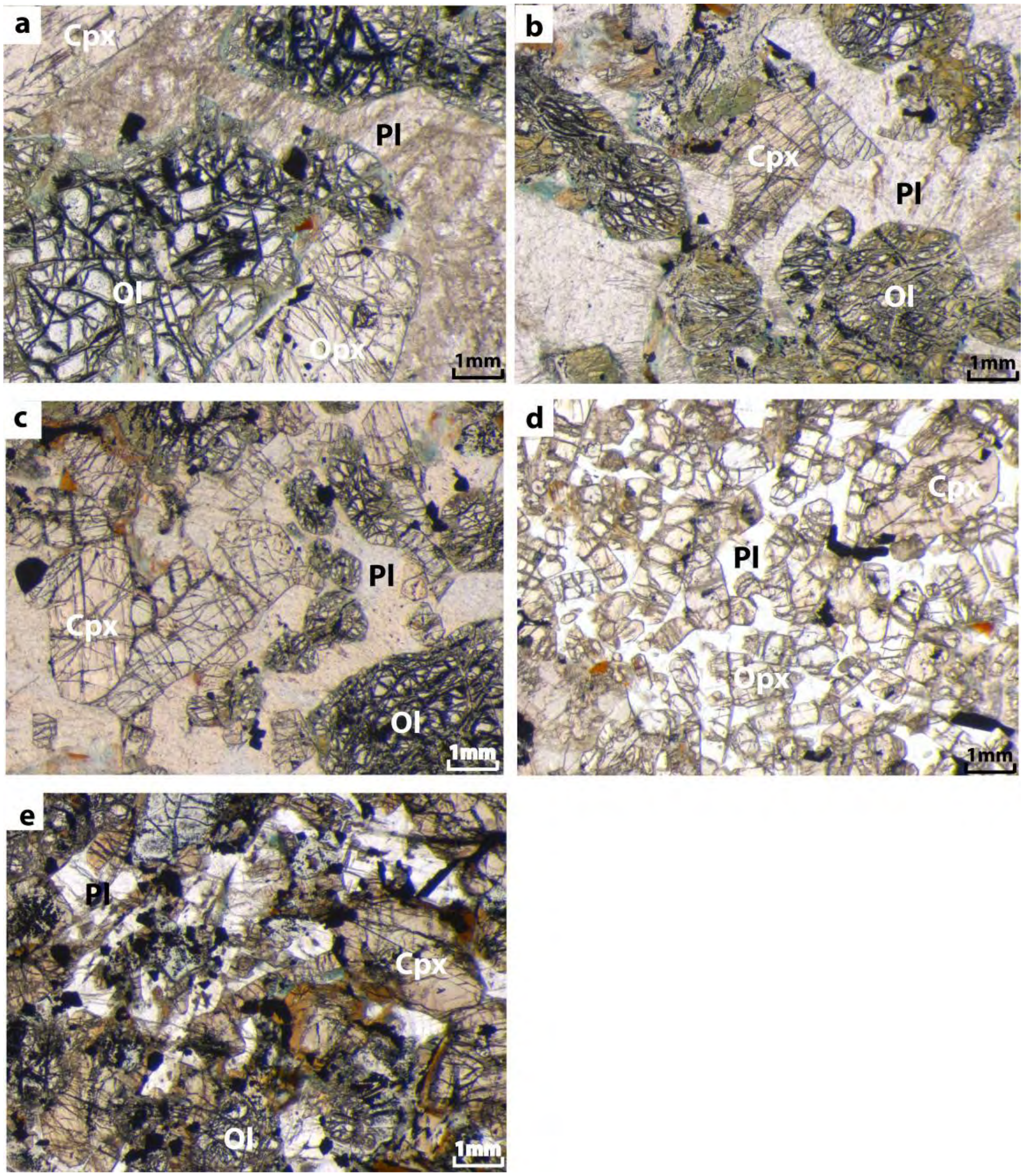

Fig.7 Photomicrographs showing typical textures of the main rock types. Photos (a) Feldspathic peridotite (b) melatrocotlite (c) melagabbro (d) gabbronorite (e) olivine gabbro

Melagabbro (Fig.7c) consists of 30-40% cumulus olivine (0.5~3 mm), 30-45% cumulus pyroxene and 25-40% cumulus plagioclase. Olivine occurs as small as inclusions in pyroxene and plagioclase or relatively large crystals intergrown with pyroxene and plagioclase.

Olivine-free gabbronorite (Fig.7d) is composed of euhedral pyroxene and plagioclase, showing preferred orientation. Pyroxene is present as large crystals and plagioclase normally occurs as euhedral to subhedral tabular crystals.

Olivine gabbro (Fig.7e) consists of 20-40% cumulus olivine (< 2 mm), 40-50% cumulus pyroxene (< 1.5 mm) and 20-40% cumulus plagioclase (< 1.5 mm). Unlike other units, the olivine gabbro unit has very low sulfide concentration but high percentages of ilmenite and hematite.

Baddeleyite U-Pb dating

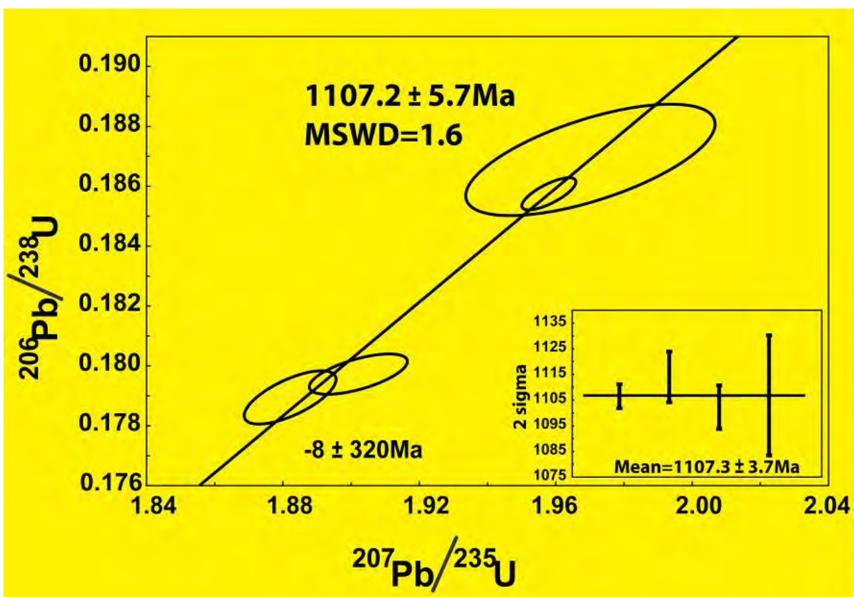

Fig.8 U-Pb isotopic data of baddeleyite from Eagle intrusion

Results of U-Pb isotopic analysis for four abraded baddeleyite crystals and one unbraded zircon crystal from feldspathic peridotite are listed in Table 1 and illustrated in Fig. 8. The four baddeleyite fractions are concordant, but the zircon grain is discordant. The zircon grain defines a $^{207}Pb/^{206}Pb$ age of

2623.3 Ma, which is consistent with the age of Archean basement of the Baraga basin. The weighted average of the $^{207}Pb/^{206}Pb$ ages for the four baddeleyite fractions is 1107.3±3.7 Ma. All baddeleyite fractions together yield a concordant age of 1107.2±5.7 Ma. The Eagle intrusion is now recognized as the second oldest intrusion in the southern part of the MRS and correlates with the eruption of the Siemens Creek volcanic suit and Mamainse Point volcanic suit (Fig.9).

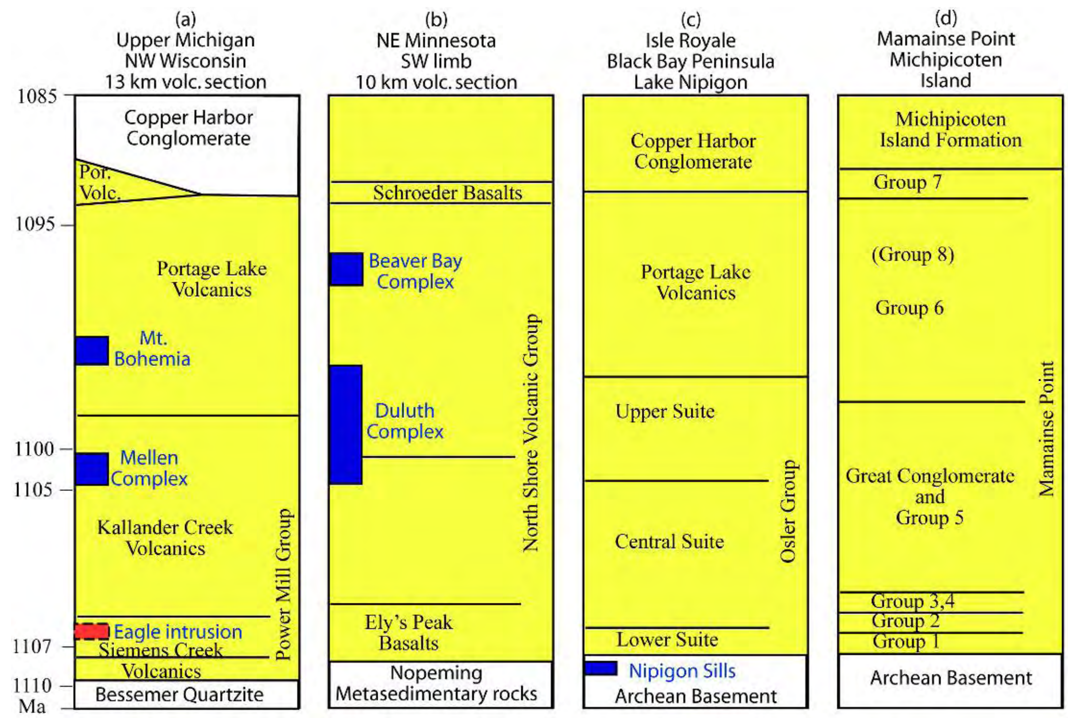

Fig.9 Chronostratigraphic correlation diagram for volcanic and plutonic rocks in western and eastern Lake Superior (after Davis and Green, 1997; Nicholson et al., 1997)

Stratigraphic variations of olivine composition, whole rock Zr/Y and La/Yb ratios and $\delta^{34}S$

The variation in the compositions of olivine in different rock types of the Eagle intrusion has been examined. The Fo contents of olivine in the sulfide-poor samples from the Eagle intrusion vary between 85 to 76 mod%. The contents of Ni in olivine are from 1,300 to 1,400 ppm. Compared to olivine from the olivine gabbro unit, olivines from other rock units are significantly depleted in Ni and exhibit a positive Fo-Ni correlation that is characteristic of fractional crystallization. In drill core 03EA034, the Fo contents of olivine decrease progressively with height in the melagabbro unit (Fig.10), stay relatively constant in the overlying melatroctolite unit, and reverse in the feldspathic peridotite unit.

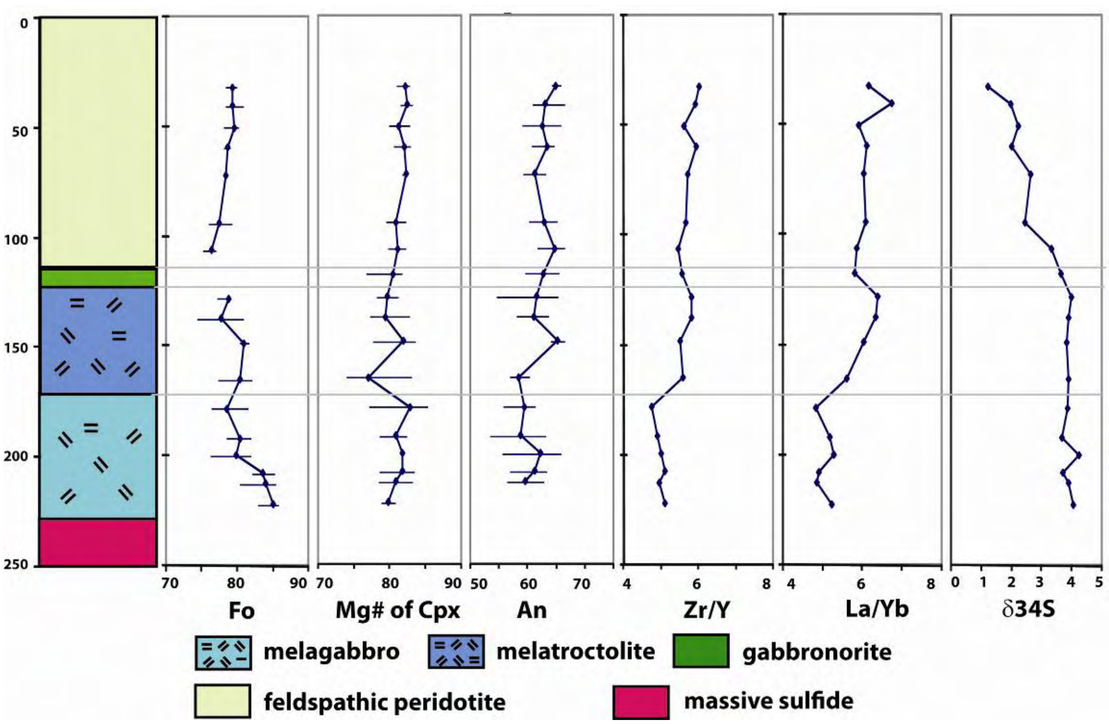

Fig.10 Stratigraphic variations of olivine composition, $Mg^{\#}$ of clinopyroxene, plagioclase An number, incompatible element ratios, and S isotope in drill core 03EA034

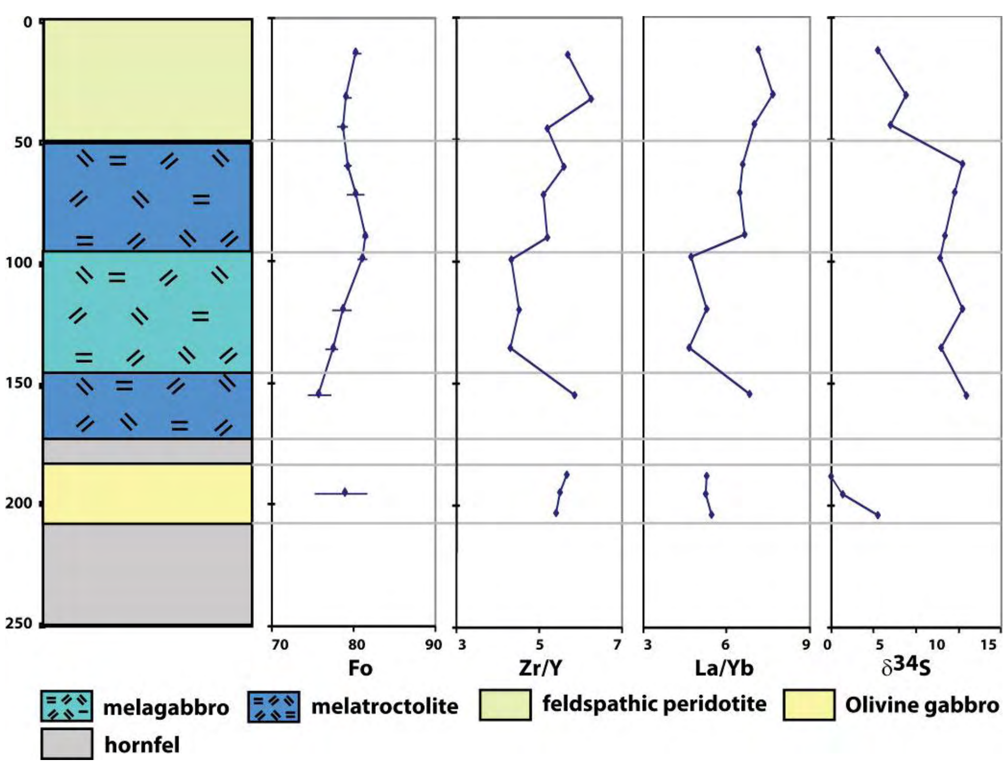

Fig.11 Stratigraphic variations of olivine composition, incompatible element ratios, and S isotope in drill core YD0106

The melagabbro unit is characterized by relatively low Zr/Y and La/Yb and elevated $\delta^{34}S$ values. The melatroctolite unit has similar $\delta^{34}S$ but distinctly higher Zr/Y and La/Yb ratios than the melagabbro. The Zr/Y and La/Yb ratios of the peridotite unit are similar to the underlying melatroctolite unit but the peridotite has distinctly lower $\delta^{34}S$ values. In the stratigraphic diagram (Fig.10 and Fig.11), $\delta^{34}S$ values are consistent from melagabbro through melatroctolite before a successive decrease towards the top of feldspathic peridotite.

Controls on whole rock compositions

In the plots of MgO versus FeO and MgO versus Al_2O_3 (Fig.12), the compositions of rocks from the Eagle intrusion are controlled by abundances of olivine and trapped liquid.

Figure 13 illustrate chondrite-normalized trace element patterns for the Eagle intrusion and country rock. The slopes of trace element for Archean gneiss and Proterozoic sedimentary rock are much steeper than those of the Eagle intrusion. Feldspathic peridotite, melatroctolite, melagabbro and gabbronorite units generally have similar trace element slopes. The olivine gabbro unit has higher trace element abundances than the other rock types in the Eagle intrusion. All rock samples from the Eagle intrusion exhibit a negative Nb anomaly which is characteristic of crustal contamination.

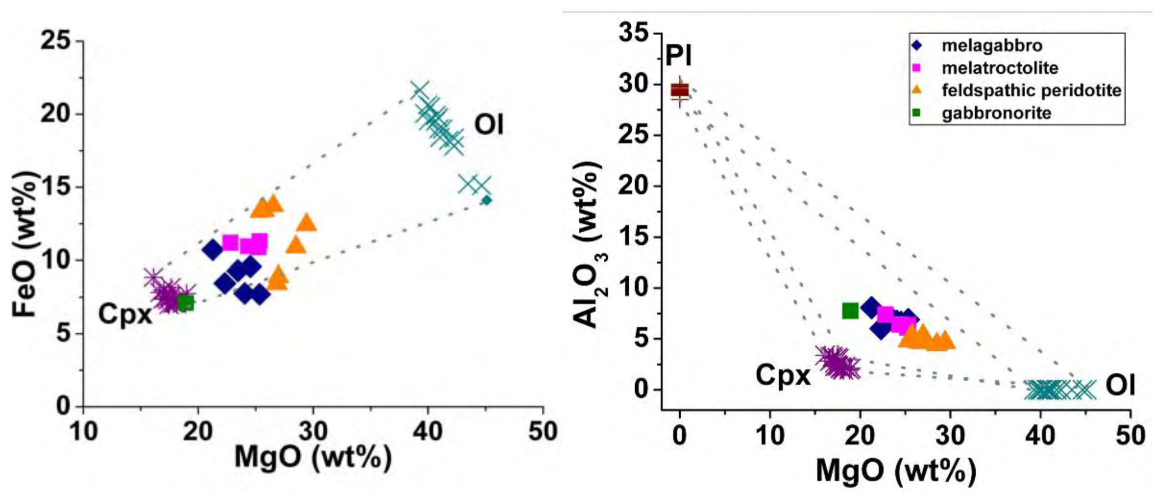

Fig.12 Variations of major elements, olivine, clinopyroxene, and plagioclase in Eagle intrusion

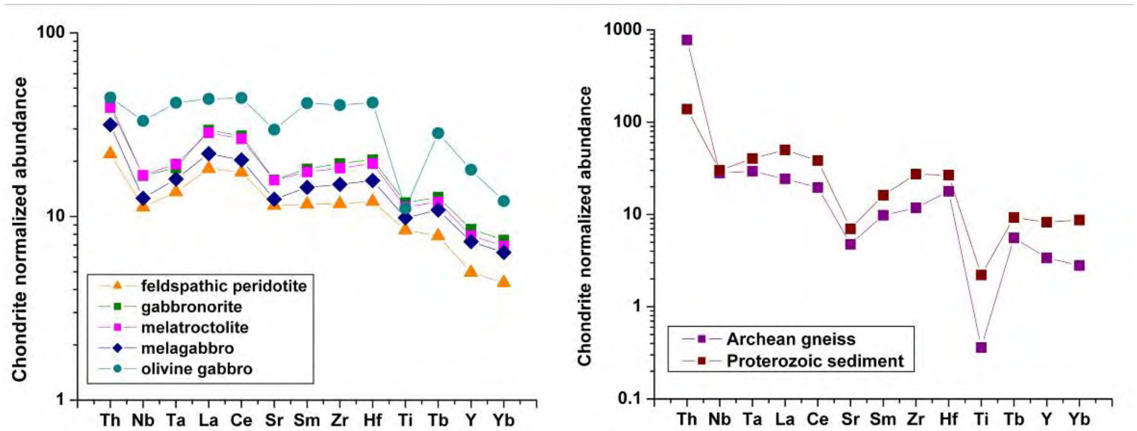

Fig.13 Trace element abundance patterns for samples from (a) Eagle intrusion and (b) country rock, normalized to chondrite (values from McDonough and Sun, 1995)

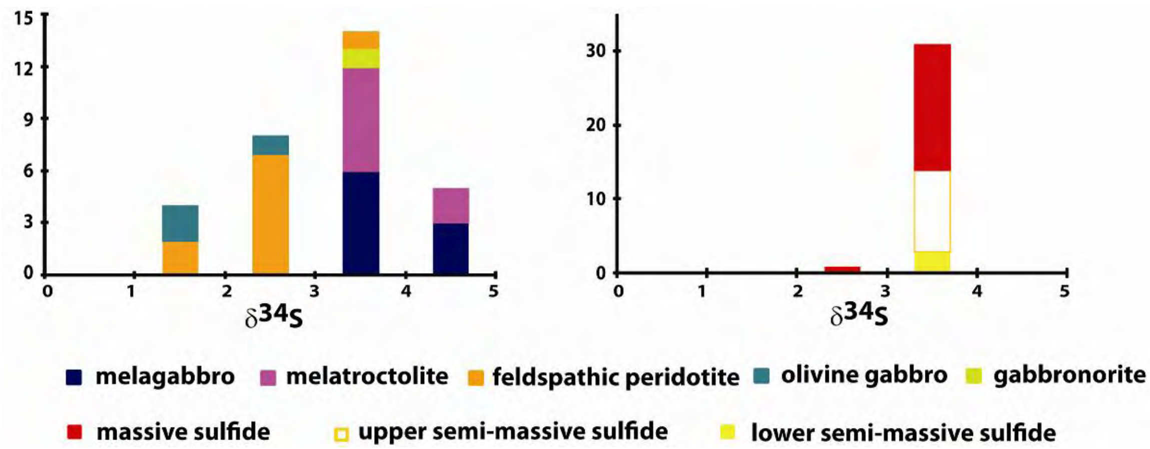

Fig.14 Frequency diagram illustrating Sulfur isotopic values of (a) feldspathic peridotite, melatrocotlite and melagabbrounits and (b) semi-massive and massive sulfides

$\delta^{34}S$ values of sulfide minerals from the Eagle intrusion vary between 1.0‰ and 4.3‰. The feldspathic peridotite and olivine gabbro samples have $\delta^{34}S$ <3‰. Elevated $\delta^{34}S$ values ranging from 3.6‰ to 4.3‰ are present in the melagabbro and melatroctolite units. Semi-massive and massive sulfide samples also have elevated $\delta^{34}S$ values.

Discussion

Multiple pulses of magma and genetic relations

The negative Fo-Ni correlation of olivine in melagabbro, melatroctolite, and feldspathic

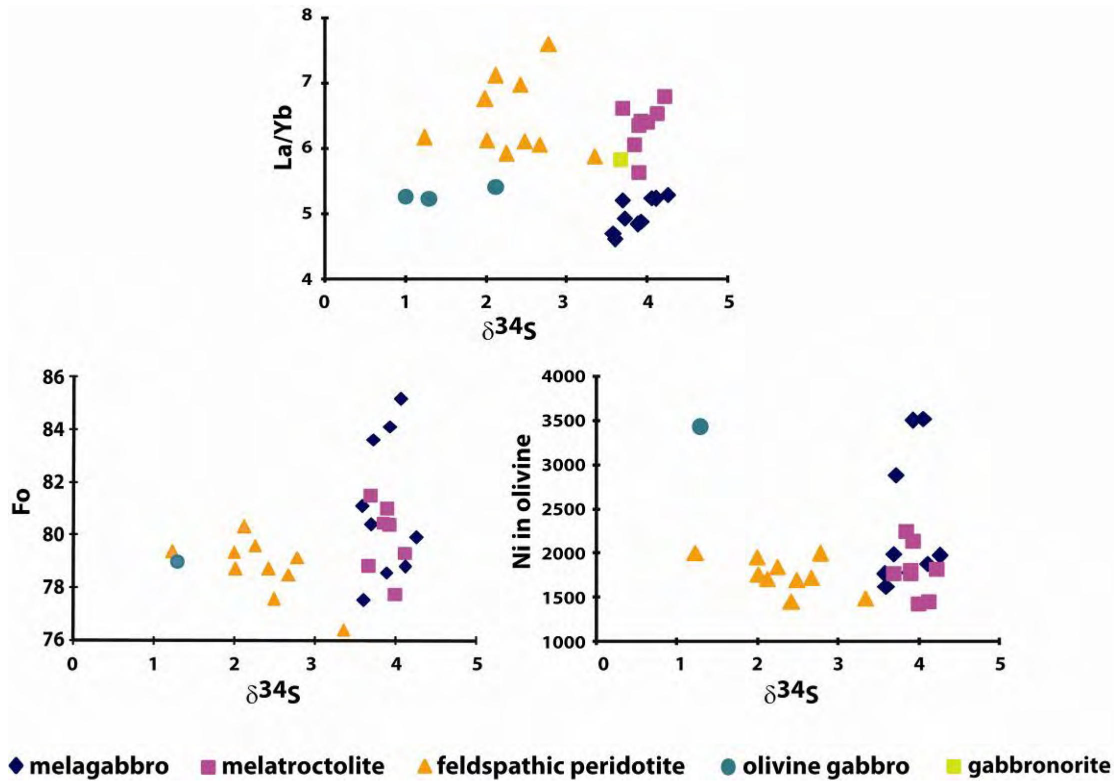

Fig.15 Plots of $\delta^{34}S$ versus incompatible element ratios and olivine composition

peridotite units is consistent with fractional crystallization. However, these different rock units have different La/Yb ratios and/or $\delta^{34}S$ values (Fig.15). These variations are likely related to different degrees or different types of crustal contamination. The lack of systematic variations in La/Yb ratios and $\delta^{34}S$ values with rock type (Fig.10) suggests that in situ contamination is not the main reason for the variations. It is more likely that those variations resulted from contamination at depth. The olivine gabbro unit has distinctly higher Ni content, which requires a Ni undepleted magma, unlike the depleted magma that formed other units. All these data suggest that at least three parental magmas were involved in the development of the Eagle intrusion: a Ni-undepleted magma, a Ni-depleted magma with $\delta^{34}S$ <3‰, and a Ni-depleted magma with $\delta^{34}S$ >3‰. They are likely related to each other by a differentiation process in a staging chamber such as: olivine crystallization, sulfide segregation or lack of sulfide segregation, or variation in crustal contamination history. Based on S field relations, it appears that Ni undepleted magma for the olivine gabbro unit intruded first, followed by the Ni-depleted magma with $\delta^{34}S$ <3‰ to form the feldsapthic peridotite unit, and finally by Ni-depleted magma with $\delta^{34}S$ >3‰ to form the melatroctolite and melagabbro units. Variations of La/Yb in each of these magmas suggest that additional, variable contamination took place during magma ascent and emplacement.

Sulfide saturation and concentration

The association of Ni depletion in olivine with elevated $\delta^{34}S$ values in coexisting sulfides is consistent with the interpretation that sulfide saturation was caused by the addition of crustal S. However, some samples with Ni depleted olivine do not have elevated $\delta^{34}S$ values. This may be due to variable $\delta^{34}S$ value in the contaminant, or contamination with S-poor country rocks. The abundance of sulfide in the Eagle intrusion far exceeds the cotectic ratio during olivine crystallization. Some mechanism of sulfide concentration was required during magma emplacement. We envision that immiscible sulfide liquid droplets were carried along with olivine crystals by magma from a staging chamber. They settled out at the entrance of the subvertical feeder to the Eagle chamber due to a sudden decrease in velocity. In this model, the Eagle intrusion was a wider part of a dynamic conduit system that fed magma to overlying dykes or sills.

Parental magma characteristics

The FeO/MgO ratio of a parental magma can be estimated by using $K_D=(FeO/MgO)_{olivine}/(FeO/MgO)_{liquid}=0.3$ (Roeder and Emslie, 1970). The calculated FeO/MgO for most primitive olivine from the Eagle intrusion is 1.04, which is similar to the values of picritic basalts in the LSCV suite and Group 1 of Mamainse Point. The Al_2O_3 contents of the liquids in equilibrium with spinels in the intrusion estimated using the relation of $(Al_2O_3)_{spinel} = 0.035(Al_2O_3)^{2.42}$ (Al_2O_3 in wt.%) by Maurel and Maurel (1982) are from 8.41 to

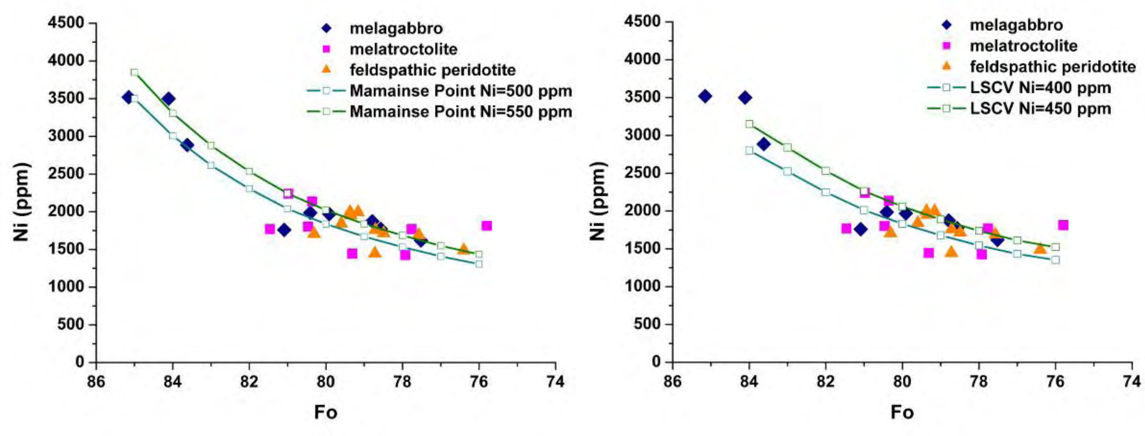

Fig.16 Modeling curves of olivine fractionation with variable initial Ni contents

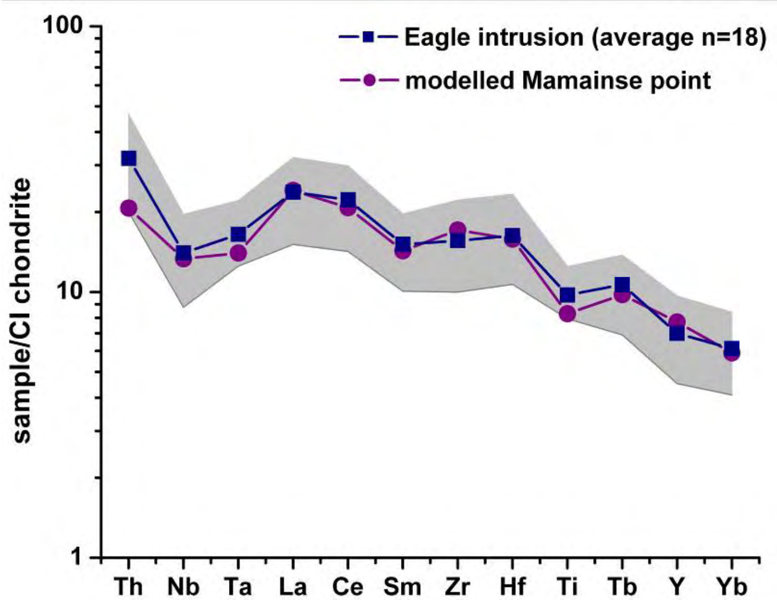

Fig.17 Trace element abundance patterns for average Eagle intrusions, and volcanic rocks (data from Shirey et al., 1994). Model trace element compositions calculated from group 1 of Mamainse Point.

10.87 wt%. These values are also similar to those of picritic basalts in the LSCV suite and Group 1 of Mamainse Point. These similarities permit us to use the average compositions of picritic basalts to simulate fractional crystallization for the Eagle intrusion using the MELTS program by Ghiorso and Sack (1995). The results for olivine and trace element is shown in Fig.16 and Fig.17, modeled trends match the observed values well.

Summary

Mineral chemistry, whole-rock composition, and S isotopes indicate that the Eagle intrusion formed by multiple pulses of magma. The different magma pulses are different in the degrees of fractionation and type of contamination. Age correlation and phase relations suggest that the parental magma of the Eagle intrusion is similar to pictitic basalts found in the Lower Siemens Creek volcanic suite and the group 1 basalts at Mamainse Point, which both erupted during the early development of the Midcontinent rift system.

The results of numerical modeling using the MELTS program indicate that the average picritic basalt can produce mineral assemblages and mineral compositions similar to those observed in the Eagle intrusion. Our current understanding of sulfide mineralization in the Eagle intrusion is that a mantle-derived, high-MgO basaltic magma rose to a staging magma chamber, crystallized olivine and segregated immiscible sulfide droplets due to contamination with sulfide-bearing country rocks. The olivine- and sulfide- charged magma was then pushed up to a higher level at Eagle by new surges of magma into the staging chamber. Olivine and immiscible sulfide droplets became concentrated in the wider part of the Eagle conduit system where the silicate liquid continued to ascend. This process may have been repeated at least twice.

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Eagle Project Area Quaternary Geology and Hydrostratigraphy*

With the exception of the Peridotite outcrops in the Project area, the bedrock surface across the Plains is mantled by unconsolidated glacial deposits from the Quaternary period continental glaciation of the region. This surface forms the base of the Quaternary deposits. Hydrologically, this surface is considered to create a boundary to the movement of groundwater within the unconsolidated materials.

The observed thickness of Quaternary deposits ranges from 0 ft (at the Peridotite outcrops) to greater than 200 ft. The deposit thickens in all directions away from the Peridotite outcrops, with the greatest thickness observed east and west of the Project area. The Quaternary deposits that define the Plains then thin toward the north and south, terminating at a boundary that is approximately coincident to the boundaries of the Baraga Basin metasedimentary rocks adjacent to the Archean bedrock formations that outcrop north and south of the Plains. Surficial geology is illustrated in Figure 1.

A general hydrostratigraphic correlation nomenclature system was developed for the EBS and is summarized below.

Surface Soil Layer

A surface soil layer (black color with organic material and tree litter) was identified at most drilling locations. This layer is generally less than 1 ft thick (and mapped regionally as 0-2 in. thick on the Plains) and is classified as a sandy organic soil). Thin surficial layers of peat have also been identified in the area directly overlying the Eagle deposit ore body.

Outwash and Beach Deposits (A Zone)

The outwash and beach deposits are comprised of well-sorted, stratified fine- to medium-grained sand, with some gravel and minor quantities of silt and clay (less than 10%). The sand fraction of this material appears to be predominantly rounded quartz with trace to minor amounts of angular and sometimes platy mafic or fine-grained sedimentary rock grains. The unsaturated portion of this deposit is typically red to reddish brown and the saturated portion is brown. These surficial deposits are mapped regionally as having very rapid water infiltration rate characteristics (greater than 10 in./hr) (Twenter 1981). An unconfined water table defined as the A zone hydrostratigraphic unit occurs in the saturated portion of this deposit.

The unsaturated zone is very thin in the southern portion of the Plains, where a large wetland complex exists. The unsaturated portion of the A zone then thickens significantly towards the northern edge of the Plains (up to 100 feet thick at wellQAL009 A/D northeast of the Peridotite outcrop). Generally a fining downward sequence is found in the A zone, with the fine sand fraction increasing with depth. A Zone groundwater elevation contours are shown in Figure 2.

Transitional Deposit (B Zone)

A gradational contact exists between the A zone outwash sand and a deeper transitional zone that contains a mix of fine sand, silt and clay, and typically continues to fine downward to predominantly silt and clay. While the A zone outwash and this transitional deposit may both be derived from melt water processes and could be lumped as outwash, the grain size characteristic change from predominantly sand to predominantly silt and clay. This transition is considered significant to primary conditions affecting groundwater flow as it indicates a decrease in permeability of the Quaternary formation from the coarse grained material to the fine-grained material.

Directly above the Eagle deposit, the A zone coarse-grained materials are very thin (generally less than 5 ft in thickness) and the B zone fine-grained deposits form the bulk of the Quaternary deposits. As a result this area contains much more poorly drained surface soil and wetlands.

Lacustrine Deposit (C Zone)

A laterally extensive, massive clay deposit was identified in samples from most borings, and is found to be thickest south of the Peridotite outcrops, and thinnest north of the outcrops towards the north terrace. The clay deposit is easily recognized in soil sample cores as lean clay with medium to high plasticity. In some core samples it appears to be a massive deposit, while in other locations it contains thinly laminated and stratified layers of silt and clay. A sharp contact is typically observed at both the top and bottom of this deposit. On average the deposit contains 98% silt and clay. This deposit is defined as the C zone hydrostratigraphic unit.

The clay deposit identified in soil borings ranged in thickness from 7-63 ft, thickest and most consistent in its elevation in the south/southeast part of the Plains (from locations QAL005A/D to QAL010A) and thinnest and less continuous towards the north and northeast, where this unit eventually pinches out near the edge of the north terrace. The pinch-out of the transitional and lacustrine deposits of the B zone near the north terrace is consistent with the glacial depositional model, as the transitional unit would be expected to pinch out at the edge of the moraine. This areal distribution pattern indicates that the fine-grained deposits were formed in ponded water between the bedrock highlands south of the Plains and glacial ice to the north, also consistent with the depositional model proposed by Segerstrom (1964).

Outwash/Ablation Till (D Zone)

A deposit of coarser-grained material was encountered beneath the C zone lacustrine deposit at most drilling locations. Samples from this deposit are predominantly fine- to medium-grained sand and are similar to samples of A zone material. This material appears to be outwash deposited prior to the glaciallake period on the Plains. This deposit is defined as the D zone hydrostratigraphic unit.

Greater heterogeneity in grain size characteristics was observed within the D zone compared to the A zone. At 2 locations (QAL004A/D and QAL005A/D) south and southwest of the Peridotite outcrop, the D zone contains a layer with significant amounts of gneiss and granitoid cobble and gravel-sized outwash material indicative of high flow velocity glacial drainage channel deposits. At other locations (QAL001A/D, QAL002A/D and the base of QAL004A/D), the D zone contains a relatively high percentage of fine sand and silt, and generally becomes increasingly finer-grained toward its base. The finer grained portion is possibly derived from direct ice melt or sublimation (ablation till), since the base of this zone is most often identified in contact with a basal till deposit, described below. This outwash deposit is also discontinuous, interrupted by shallow bedrock and pinched out between the fine-grained units above and below. This deposit was not encountered beneath the C zone at well nests QAL006A/B and QAL010A. This deposit appears to be confined or partially confined, except at location QAL009A/D where the overlying C zone clay is absent. As a result of the pinch-out of the B and C zones in close proximity to the northern edge of the Plains, the A and D zone aquifers at this location become a single unconfined system. D Zone groundwater elevation contours are shown in figure 3.

Basal Till (E Zone)

Poorly-sorted basal till consisting of boulder- to sandy-sized clasts in a fine grained matrix is the lower most Quaternary deposit material identified in samples from all but one boring (QAL004A/D). This unit is substantially thicker east (QAL009A/D), west (QAL007A/D) and southeast (QAL010A) of the Project. Bedrock is encountered at greater depths at these locations, indicating that earlier glacial moraine deposition occurred in the bedrock valleys. Boulders are commonly present along the north terrace

Lower Outwash Units (F Zone)

At 2 locations (QAL007A/D and QAL010A), lower outwash deposits were found interlayered with E zone till. Representative samples of the lower outwash material are predominantly fine- to medium-grained sand. In QAL010A these units were found to be dry. The interlayered nature of the till and lower outwash units indicates fluctuations in glacial advances and retreats during earlier glacial depositional sequences. This lower outwash deposit is defined as the F zone hydrostratigraphic unit.

*Text and figures extracted form Internal Company Report by Wiitala, D. et al. North Jackson Company.

“Kennecott Minerals Company Eagle Project” Comprehensive Summary of Hydrologic Reports”. Feb, 2006

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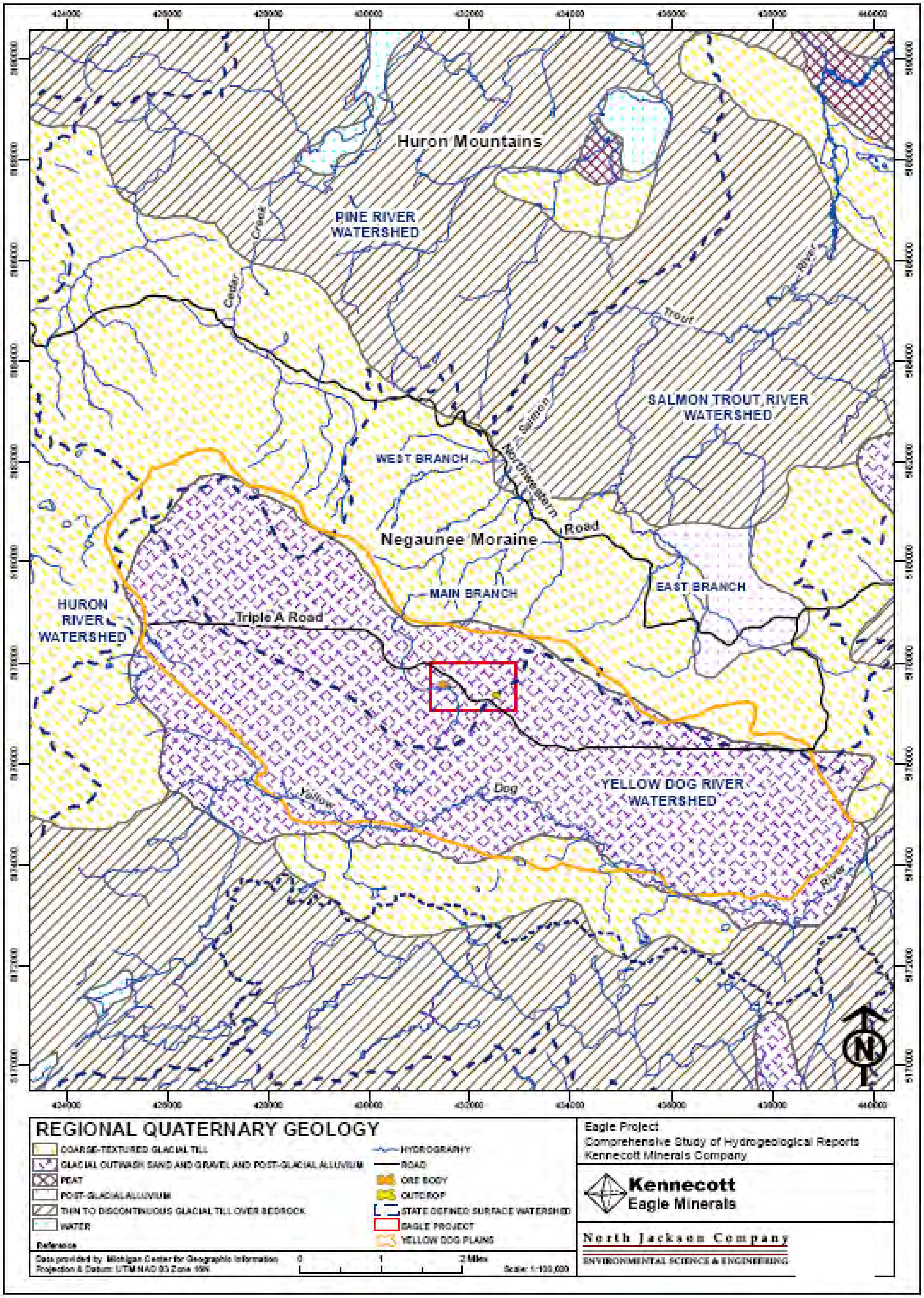


Figure 1. Regional Quaternary Geology.

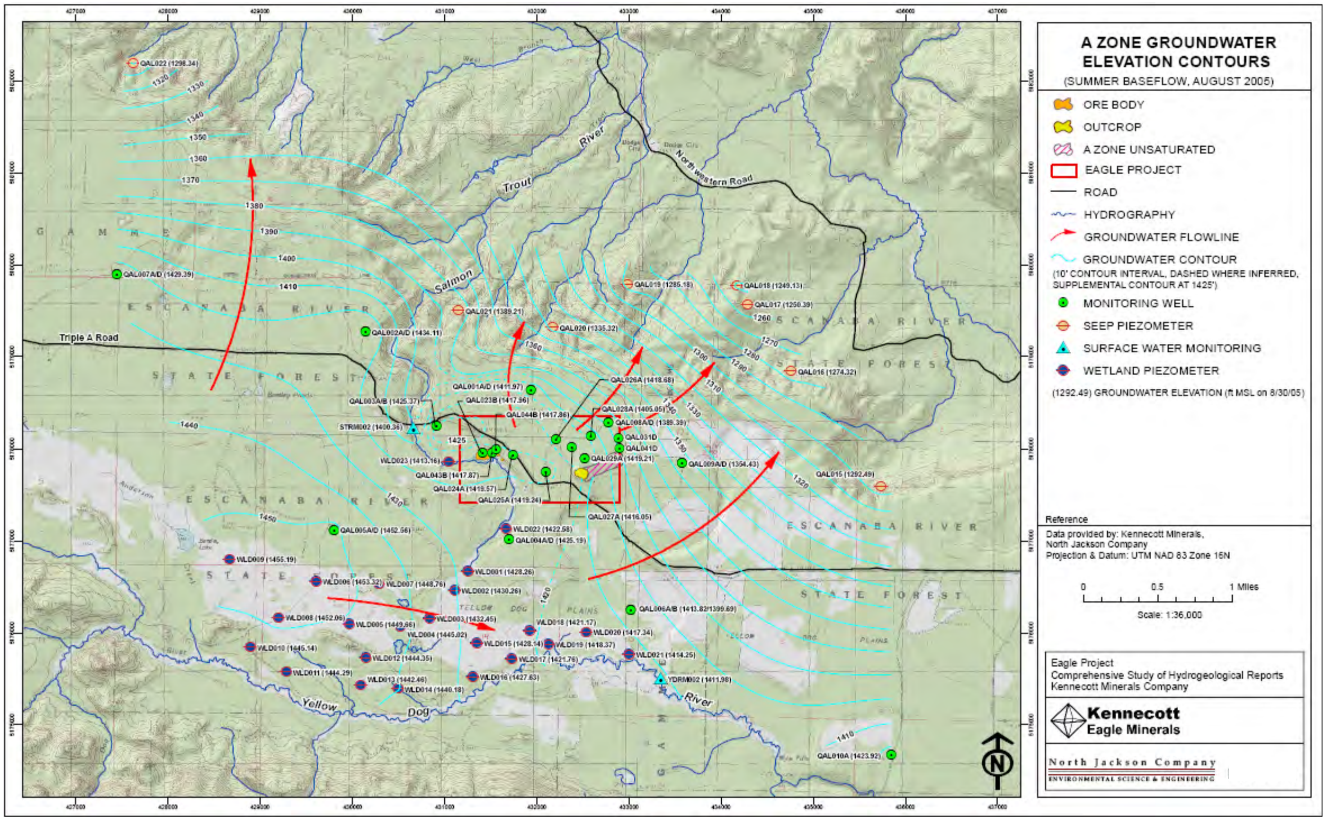


Figure 2. A Zone Groundwater Elevations (Summer Base Flow, August 2005)

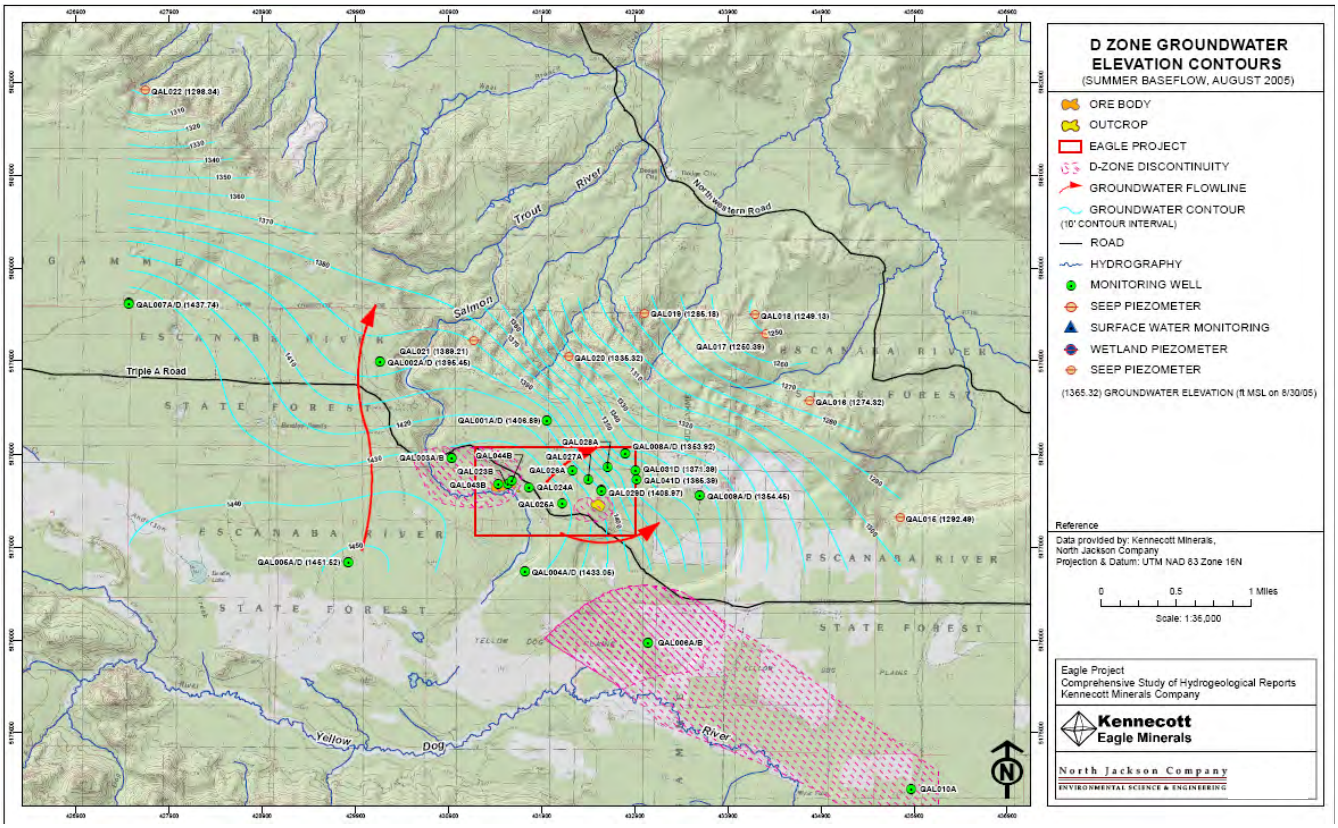


Figure 3. D Zone Groundwater elevation Contours (Summer base flow August 2005)

Eagle Project - Field Trip Stops

There are three field trip stops on the Eagle tour. Exposure in the Yellow Dog Plains is limited to two outcrops of ultramafic intrusives.

Stop 4-1) Yellow Dog Peridotite – Eastern Outcrop.
(UTM coordinates 432 440E 5 177 380N _ North side of County Road AAA)

Travel north-west from Marquette on County Road 550. Turn on to County road 510 and then on to County Road AAA. Total distance from the 550/510 intersection is approximately 12 miles. The AAA turn will be flagged. Use precaution on the 510/AAA roads as logging trucks use these narrow roads for access.

The main outcrop forms the western end of an inverted fin shaped intrusion that plunges to the east. Drilling has intersected feldspathic peridotite to a depth 720m below surface on the eastern end.

In outcrop, both the eastern and western peridotites have distinctive, reddish brown, pitted weathered surfaces with rare bright red patches indicating oxidized pyrrhotite blebs. Weathering rinds are typically less than a centimeter thick, and relatively fresh looking sulfides can be seen within a few millimeters of the surface.

Two primary lithologies, peridotite and pyroxenite, are recognized within both intrusions. Serpentinization of olivines, uralization of pyroxenes and chloritization of amphiboles are noted in thin section work.

Stop 4- 2) Yellow Dog Peridotite – East end of Host Intrusive Complex for the Eagle Deposit.

(UTM 431 720E 5 177 580N – South side of the County Road AAA)

The eastern exposure is of an olivine gabbro. This particular phase represents one of the more primitive melts as defined by sulphur isotope data. Rare disseminated sulphide mineralisation can be observed in the outcrop.

Stop 4-3) Kennecott Eagle Mineral Co Core storage Facilities

200 Echelon Drive, Negaunee. Turn Right of Highway 41 at the TV6 Studios. The Michigan State Police post is located opposite the turn off on the south side of the highway. Drive North for 200 yards and turn west through a set of large gates. The core storage buildings are located on the left hand side of the road. The turn off form the highway is located approximately 3 miles east of Negaunee. (Do not use MapQuest Directions).

A review of core from the Eagle Project and The BIC project will be available for review.

Eagle – Baraga Basin Exploration History

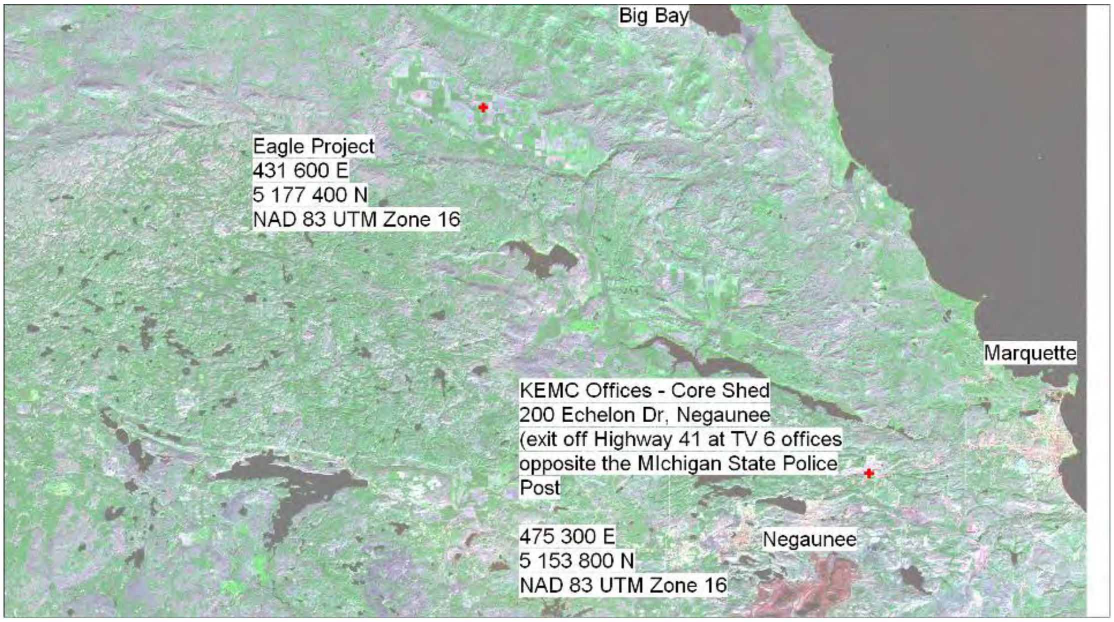
The Baraga Basin region has until recently been subject to only sporadic exploration efforts. The earliest historical accounts of exploration in the basin date back to the mid- 1800's when a group of investors tried to develop slate quarries along Slate River. Little documented exploration work took place in the Baraga basin between 1910 and 1950. During the 1950's Jones and Laughlin conducted an exploration program along the northern portion of the East branch of the Huron River, investigating uranium-silver mercury mineralization associated with a graphitic shear exposed in the river. During the 1960's and 1970's, various interests conducted exploration programs on Ford mineral lands in the Baraga Basin and the western portion of the Marquette Trough. The programs were primarily focused on uranium and zinc. The U.S. Department of Energy provided funding to drill a number of deep holes in the Baraga Basin during the 1970's presumably to provide stratigraphic information for the uranium exploration effort. Concurrently, the USGS began a bedrock-mapping program of the basin, focusing primarily on exposures in rivers, which produced an open file outcrop map with no report (Cannon, 1977).

In 1976, Michigan Technological University drilled a 31-meter hole on the east end of the Yellow Dog (East Eagle) outcrop. The hole bottomed in coarse-grained peridotite with only traces of sulfide. In 1979, the Michigan DNR, in conjunction with the USGS, published a report on the Yellow Dog peridotite describing the results of geochemical, petrographic and geophysical studies of the peridotite (Klasner and others, 1979). The authors concluded that the anomalous sulfur and copper contents of the outcropping peridotite indicate a significant potential for copper-nickel ore deposits. Kennecott Exploration started working in the region in 1991 and actively explored for sedex zinc deposits through 1994. During the course of mapping, float boulders of peridotite with sulphides were discovered that indicated the potential for magmatic Ni-Cu sulphide mineralization. Kennecott partially shifted to magmatic nickel exploration in 1995 and drilled four holes to test the Yellow Dog peridotite (East Eagle). One hole (YD95-2) intersected 10 meters of moderate to heavy disseminated sulfide mineralization along the southern contact. Two more angle holes (YD95-3 and YD95-4) collared on the east end of the Yellow Dog East outcrop demonstrated the peridotite widened to the east but only intersected a meter or two of weak sulfide mineralization along the north and south contacts.

The Michigan program was put on hold in the summer of 1996 and the Crystal Falls Office was closed as Rio Tinto reorganized the newly merged CRA, Kennecott and Rio Tinto exploration groups. The land position around Eagle was reduced to a core group of private and state leases in 1997 and 1998.

Interest in the project was regenerated in 2000 through the persistent efforts of Kennecott geologist Dean Rossell who recognized the potential for the region to host significant nickel mineralization in light of recent published papers on Norils'k and Voisey's Bay. The current nickel exploration program was started late in 2000. Drilling at East Eagle in July 2001 intersected **30 meters** of disseminated, net textured and massive sulfides averaging **1.03% Ni** and **0.75% Cu** (YD01-01) and one of three holes on the east end of Eagle intersected **85 meters** of disseminated sulphides averaging **0.6% Ni** and **0.5%Cu** (YD01-06).

2002 drilling at Eagle targeted the center of a magnetic anomaly defined by ground surveys in 2001. The first hole, YD02-02, intersected **84.2 meters** of massive pyrrhotite-pentlandite-chalcopyrite averaging **6.3% Ni** and **4.0% Cu**, firmly establishing the presence of economic grade and width mineralization at Eagle. Subsequent definition drilling continued through the summer and fall of 2002 and has continued through to the present.



References:

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Klasner, J.S., Snider, D.W., Cannon, W.F., and Slack, J.F, 1979. The Yellow Dog Peridotite and a possible buried igneous complex of lower Keweenawan age in the northern peninsula of Michigan. State of Michigan, Dept. of Natural Resources, Geological Survey Division; Report of Investigation 24, 31 pp.

54th Annual Institute on Lake Superior Geology

FIELD TRIP 5

THE SUDBURY IMPACT LAYER AT THE McCLURE SITE

William F. Cannon
U.S. Geological Survey

Matrix supported breccia containing clasts of chert in mixed glass-clastic matrix

Introduction

Note: As this guidebook is being prepared a substantial road construction project is underway to realign County Road 510 through the area of interest. Specifically, the road is being moved several hundred feet to the west of the location shown in Figures 2 and 3 and will connect to a new bridge being constructed over the Dead River. The descriptions and outcrop locations shown in this guide are those that existed through late 2007. When the field trip is conducted in May of 2008 the outcrop and access situation may be somewhat altered.

The outcrops to the west of 510 are nearly all on land owned by Marquette County and are publicly accessible. Please observe private property boundaries to the far west and south of this area. The outcrops east of 510 are on private property to which the owners have granted access for scientific examination and reasonable sampling for research purposes.

A set of outcrops near County Road 510, about 5 miles northwest of Marquette, Michigan (Figure 5.1) provides a complete section through the layer of debris deposited as a result of the giant impact at Sudbury, Ontario, which occurred about 500 km to the east at 1850 Ma . The Sudbury layer here is a breccia and sandstone unit about 40 m thick, which lies on banded iron-formation and is overlain by pyritic black slate. Outcrops include: 1) the basal contact of the layer that consists of large rip-up clasts of the underlying iron-formation; 2) exposures of matrix-supported breccias in which most large fragments are chert, but many smaller fragments are impact glasses; 3) an upper massive sandstone with minor chert clasts and glass particles; and 4) the upper contact with black slate. The McClure site is the best-exposed section of the Sudbury layer currently known in Michigan and also is the thickest. In addition it is the closest exposure to the impact site at Sudbury. Because there are no preserved rocks of 1850 Ma age between here and Sudbury, the McClure site contains the most proximal ejecta that is likely to be found.

General geology

The McClure site is in the Dead River Basin, a structural outlier of Paleoproterozoic strata surrounded by Neoarchean crystalline rocks. The strata consist entirely of various informal units of the Michigamme Formation. The Sudbury layer at McClure was mapped as a chert conglomerate by W.P. Puffett (1974) who provided a detailed outcrop map of the immediate site as well as a 1:24,000 scale map of the Negaunee Quadrangle on which the layer was shown as a map unit. The unit was extended further west into the adjacent Negaunee SW quadrangle by Clark and others (1975).

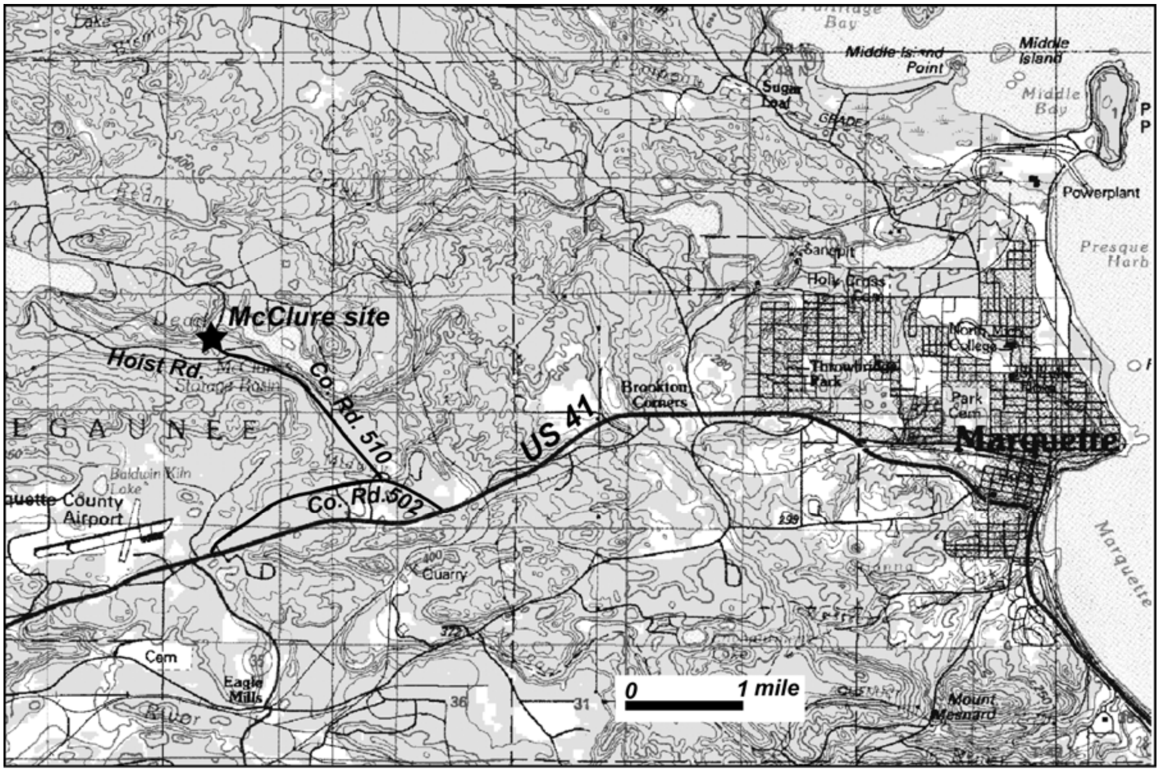

Figure 5.1. Map showing location of the McClure site.

The Sudbury layer at McClure lies within a north-facing monoclinal succession of sedimentary rocks, all informal members of the Michigamme Formation, a part of the Baraga Group, which lies unconformably on Neoarchean granitic rock (Figure 5.2). The Michigamme Formation consists of a basal unit of quartzite and conglomerate, probably equivalent to the Goodrich Quartzite of the Marquette Range. The unit is about 60 meters thick and grades upward into a 150-200 meter-thick unit of impure quartzite and argillite. A 60 meter-thick unit of banded chert-hematite-goethite iron-formation overlies the impure quartzite and is the unit on which the Sudbury impact layer was deposited. Overlying the Sudbury layer with an apparent gradational contact is pyritic black slate. Thus the Sudbury layer at the McClure site lies about 250-300 meters above the base of the Baraga Group. This field trip will examine a set of outcrops that exposes a cross section of the impact layer as well as the upper and lower contacts with the adjacent stratigraphic units (Figure 5.3).

Description of the Sudbury impact layer

The rock layer here referred to as the Sudbury impact layer has been studied and described for nearly a century, but only in 2006 was it documented to be an impact-related unit. The most complete previous description was by Puffett (1974) who mapped and described the unit as a chert conglomerate containing many fragments of volcanic rocks. He interpreted it to have originated "during a period of volcanism in which thick tuff deposits accumulated, then was disturbed by landslides or other gravity-activated mechanisms that dumped material into the site of deposition." Puffet clearly recognized the essentially instantaneous deposition of this massive, graded unit and the unusual mixture of volcanic fragments, chert clasts, and quartz sand grains, and called upon a reasonable combination of terrestrial geologic processes to have formed it.

As an historic note, my former colleague, Willard Puffet, showed these outcrops to me in September 1967 on one of my first days of employment with the USGS in the Marquette Field Office. He asked if I could help explain these unusual features. Fortunately, he didn't give me a deadline.

Our current interpretation of the nature and origin of the Sudbury layer at the McClure site is based on examination of the outcrops and standard thin section petrography of a suite of samples collected at a regular interval across the unit. The definitive microscopic evidence for a link between the breccia bed at McClure and a major impact is the documentation of shock metamorphic features within it. A small percentage of the quartz grains within the breccia matrix contain relict planar deformation features (pdf's) indicative of the extreme pressures generated instantaneously during a hypervelocity impact (Figure 5.4 A,B). There are no terrestrial processes capable of generating pressures remotely within the range needed to form these distinctive features. Figure 4 illustrates two examples of quartz grains with two sets of relict pdf's. These planar features were originally lamellae of impact-generated glass resulting from breakdown of the quartz lattice along preferred crystallographic planes by extreme shock pressures. Over time the glass has recrystallized to quartz, but has left behind planes rich in inclusions, relict pdf's, that mark the original shock lamellae.

At the McClure locality the identification of true pdf's is complicated by the occurrence of extraordinarily abundant Bohm lamellae, features produced by terrestrial deformation (sometimes referred to as metamorphic deformation lamellae). Apparently the temperature and pressure of deformation was optimum for development of these lamellae. Like pdf's they occur as parallel lamellae within quartz grains (Figure 5.4 C,D) and can be difficult to distinguish with certainty from pdf's. The most characteristic Bohm lamellae are thin planar features in which the quartz lattice has been slightly distorted so that the lamellae have extinction angles that vary by a few degrees from the host grain (seen best in Figure 5.4 C). Bohm lamellae are commonly somewhat curviplanar in contrast to unvaryingly planar pdf's, and also commonly develop at approximately right angles to boundaries between individual crystallographic domains within strained quartz grains (also seen well in Figure 5.4 C). Bohm lamellae are also common in quartz grains in the underlying quartzite and greywacke so seem clearly to have developed *in situ* during deformation of the host rocks and are not related to the Sudbury impact.

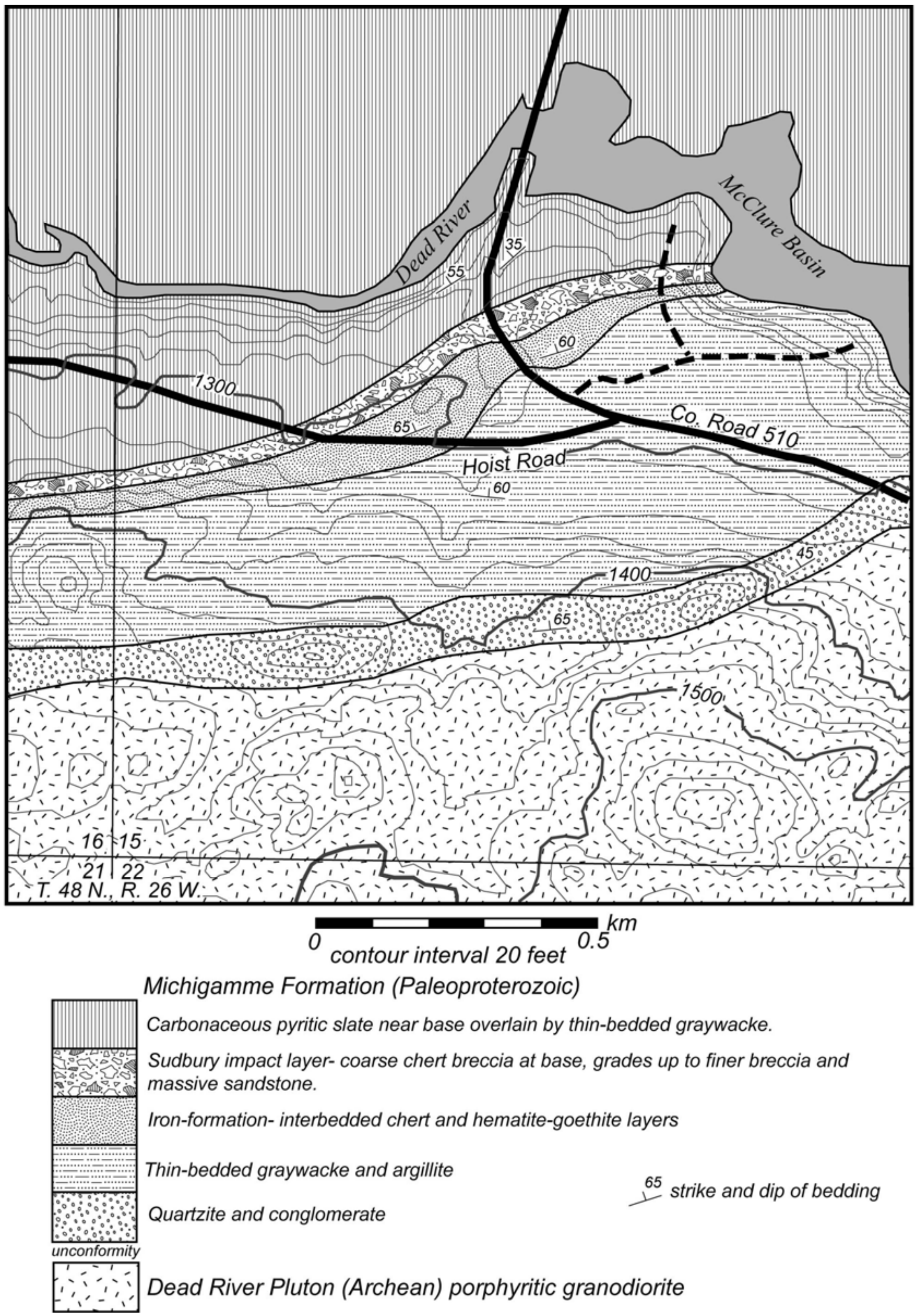

Figure 5.2. Geologic map of the area near the McClure site. Modified from Puffett (1974).

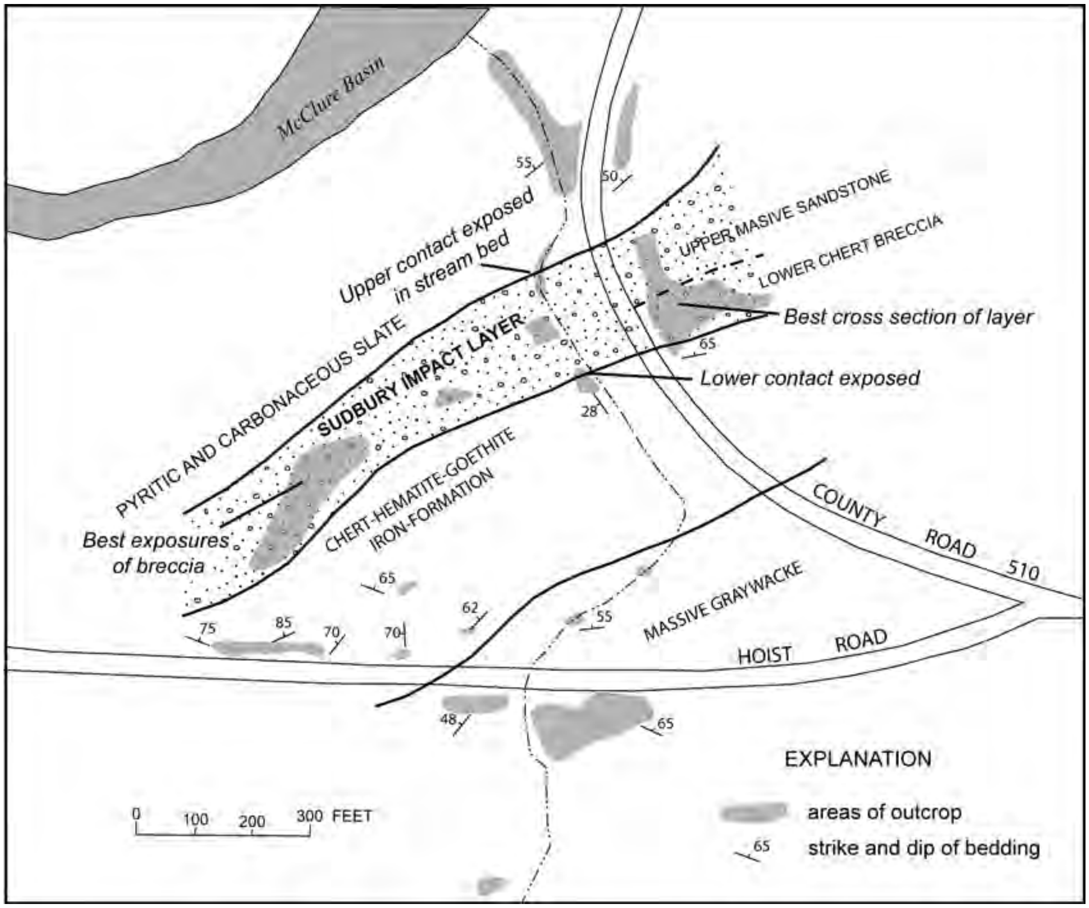

Figure 5.3. Detailed map of the McClure site. Modified from Puffett (1974). Note that the location of County Road 510 is that prior to relocation in 2007-08. The new road is not shown.

A cross section of the unit and modal compositions are shown in Figure 5.5. The most distinctive feature of the layer is the coarse chert breccia that makes up approximately the lower half of the unit. The breccia grades upward both in size and abundance of clasts, mostly chert. The basal unit is a framework of chert slabs up to a meter long surrounded by a matrix largely of clastic material and subordinate altered glass particles (Fig 5.6A). This grades up into matrix supported breccia (Figure 5.6 B,C,D,E) in which accretionary lapilli occur sparsely (Figure 5.6C). Clasts generally show little or no preferred orientation, but locally (Figure 5.6D) are well aligned. Most large clasts are chert, at least partly derived from the underlying iron-formation, but some phases have abundant exotic fragments, apparently volcanic rocks (Figure 5.6D). In some outcrops, many chert clasts have an alteration rim (Figure 5.6E) suggesting reaction between the clast and matrix. As shown by Figure 5, the breccia matrix has relatively constant composition expressed as the percentage of clastic quartz sand grains, altered glass particles, and fine groundmass. Glass particles account for 35-40% of the matrix. The glass particles are now mostly chlorite (Figure 5.7 A, B, C, E) in which relict vesicles are common. Many vesicles are flattened indicating considerable post-depositional distortion. Some particles have a complex intermixing of compositions (Figure 5.7A), possibly a result of immiscible melts. Other rock types, such as the quartzite clast in Figure 5.7F, are rare. The groundmass in the breccia matrix is aphanitic, apparently of felsic composition, and clouded with uniformly distributed opaque grains. Its nature is not clear at this point in our studies.

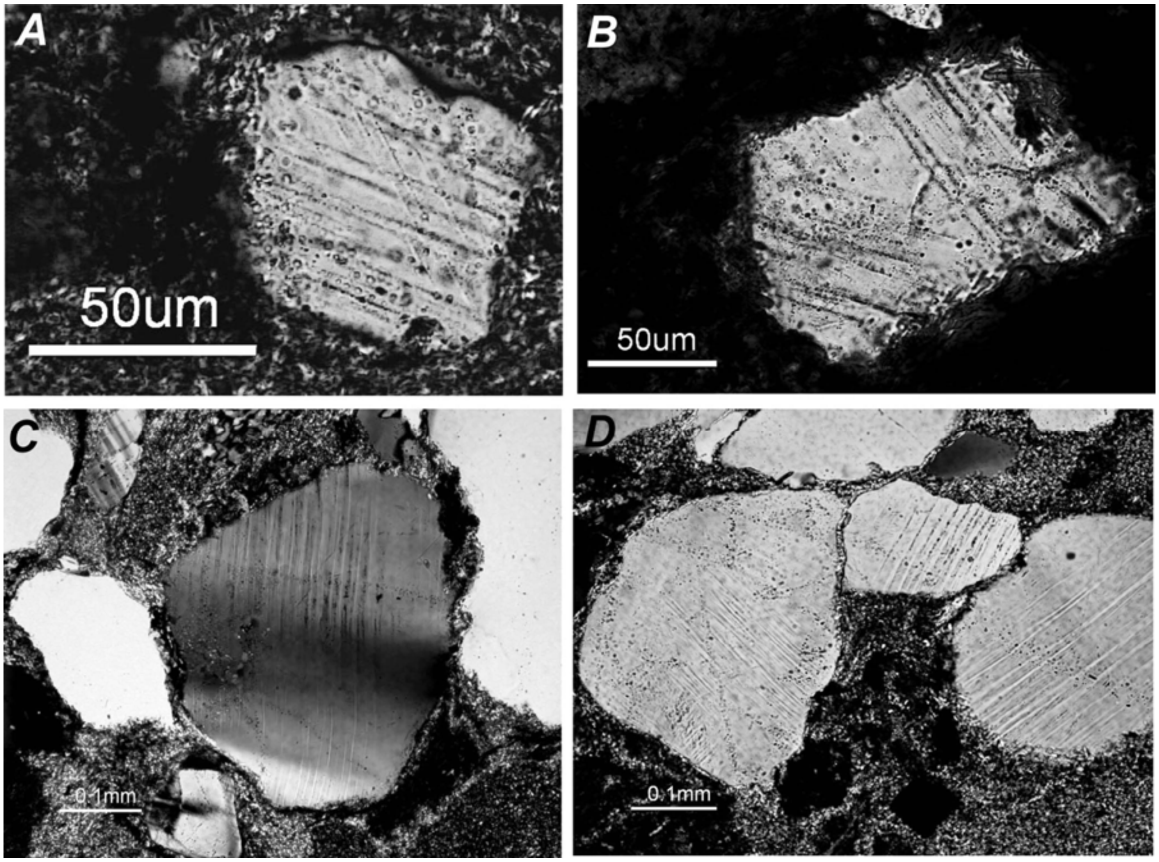

Figure 5.4. A and B- quartz grains with two intersection sets of relict planar deformation features expressed by abundant fine inclusions. These are definitive indicators of intense shock pressures. C and D- Quartz grains containing Bohm lamellae showing slight variations in extinction angles from host grains, curvilinear nature, and right angle intersections with boundaries of deformation zones in strained grains (best seen in C).

The upper part of the layer, beginning about 25 meters above the base, is a massive dark gray to black impure sandstone. Angular chert pebbles are sparse and much less abundant than in the underlying breccia. Glass particles are common but less abundant than in the breccia and average about 20% of the rock (Figure 5.7D). Rounded to subangular quartz grains are more abundant than in the underlying breccia and make up roughly 35% of the sandstone. The groundmass also differs from that of the breccia and appears to be fine clastic particles with a wide range of grain size in contrast to the very uniform groundmass of the breccia. The contact between the lower breccia and upper sandstone appears to be gradational over several meters.

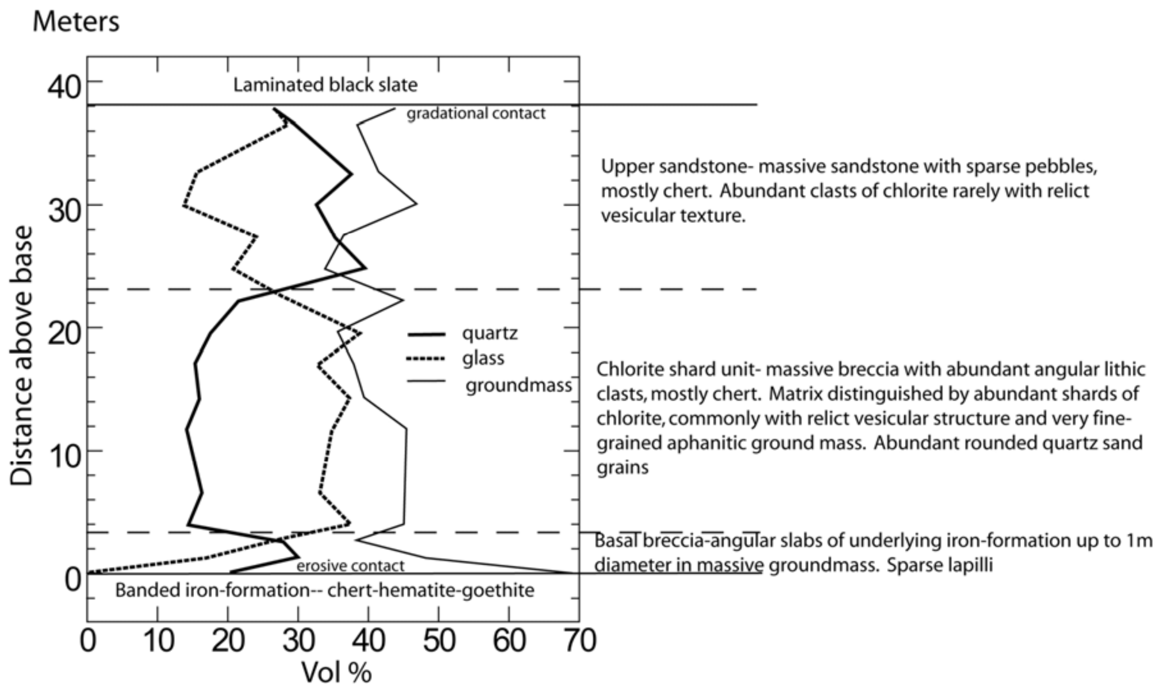

Figure 5. 5. Cross section of the Sudbury impact layer at McClure showing variations in the modal composition of the matrix of the lower breccia and the upper sandstone.

The upper contact of the Sudbury layer with overlying black slate can be seen in very small exposures in the bed of the intermittent stream that is subparallel to Co. Rd. 510. When the stream is flowing, these outcrops are largely below the shallow water. The contact appears to be gradational over a meter or two in which fine-grained sandstone gives way to laminated carbonaceous slate.

Interpretation

Several features of the Sudbury impact layer at the McClure site provide clues to the processes responsible for its deposition:

1) Shock metamorphic features provide verification that it contains ejecta from a major extraterrestrial impact. Independent age constraints place the time of deposition within a roughly 40 million year time window that includes the 1850 Ma Sudbury event. No other major impact events of that age are known in the region, so a link to the Sudbury impact is deemed very likely.
2) The massive, graded and poorly sorted nature of the deposit and complete lack of internal bedding or laminations suggest the entire 40 m thickness records a single depositional event.
3) The high energy deposition indicated for the Sudbury layer is in sharp contrast to the very low energy environments indicated for the underlying even-bedded iron-formation and overlying laminated black slate. So deposition appears to be a unique instantaneous event. Both the underlying and overlying units were deposited in a marine setting with water depths greater than the depth of wave action.
4) The abundance of rounded quartz and chert sand grains throughout the unit indicates that, in addition to material ejecta from the crater at Sudbury, the unit contains a substantial component

of material that was acquired by erosion of surficial materials that existed between Sudbury and the McClure site.
5) The abundance of altered particles of glass, a very high percentage of which are highly vesicular and of mafic composition, and have complex delicate shapes suggests that the particles were not derived by erosion of older volcanic rocks, which would have produced a variety of textures and compositions, but rather formed from solidification of highly gas-charged impact-generated melts and acquired their present shapes *in situ*.
6) The very coarse breccia at the base of the unit, consisting of meter-scale slabs of the underlying iron-formation, indicates that the onset of deposition was a very high-energy event.

Although studies of the Sudbury layer here are still in the early stages, a preliminary interpretation is presented based on current observations. Deposition began in relatively deep quiet water on a substrate of banded iron-formation. The basal beds are a result of highly energetic disruption of the iron-formation and may have been produced either by erosion caused by a fast-moving mass of ejecta or by seismic disruption of the surface sediments moments before the arrival of ejecta. The seismic shock wave generated by the impact would have arrived here within a minute or two after the impact, whereas the first ejecta may have arrived a few minutes later. Spaces between iron-formation slabs are filled with a mixture of clastic grains, particles of altered glass, and sparse accretionary lapilli indicating that the ejecta arrived while there was open space between the slabs.

The remainder of the unit at McClure may record deposition from a single turbidity flow. Numerous numeric models of giant impacts have been published in recent years and all predict a rapid expansion of an ejecta cloud or ejecta curtain consisting of solid rock, impact melt, and vapor. Horizontal velocities of thousands of kilometers per hour are predicted. As this high velocity mass returns to the Earth's surface, it continues to move at high velocities as a ground surge. This surging mass is capable of eroding and transporting surficial material and eventually incorporating it into hybrid deposits consisting both of ejecta and the eroded surficial materials. The mixture of ejecta material at McClure with quartz and chert sand and larger rock fragments, largely chert derived from the nearby iron-formation, suggests that a ground surge played a significant role in its formation. A less certain aspect of the interpretation is how a ground surge would have interacted with the ocean water that covered the area at the time. Did the surge ride atop the water column and eventually sink through it as it lost velocity, or did the entire water column become part of the surge. If the basal breccia is a result of erosion by the surge, then the water column must have been incorporated into the surge. If the breccia is a result of seismic disruption and later infiltration by ejecta an ocean-overriding mechanism is possible.

Much additional work is required to understand the intriguing features so well exposed at the McClure locality.

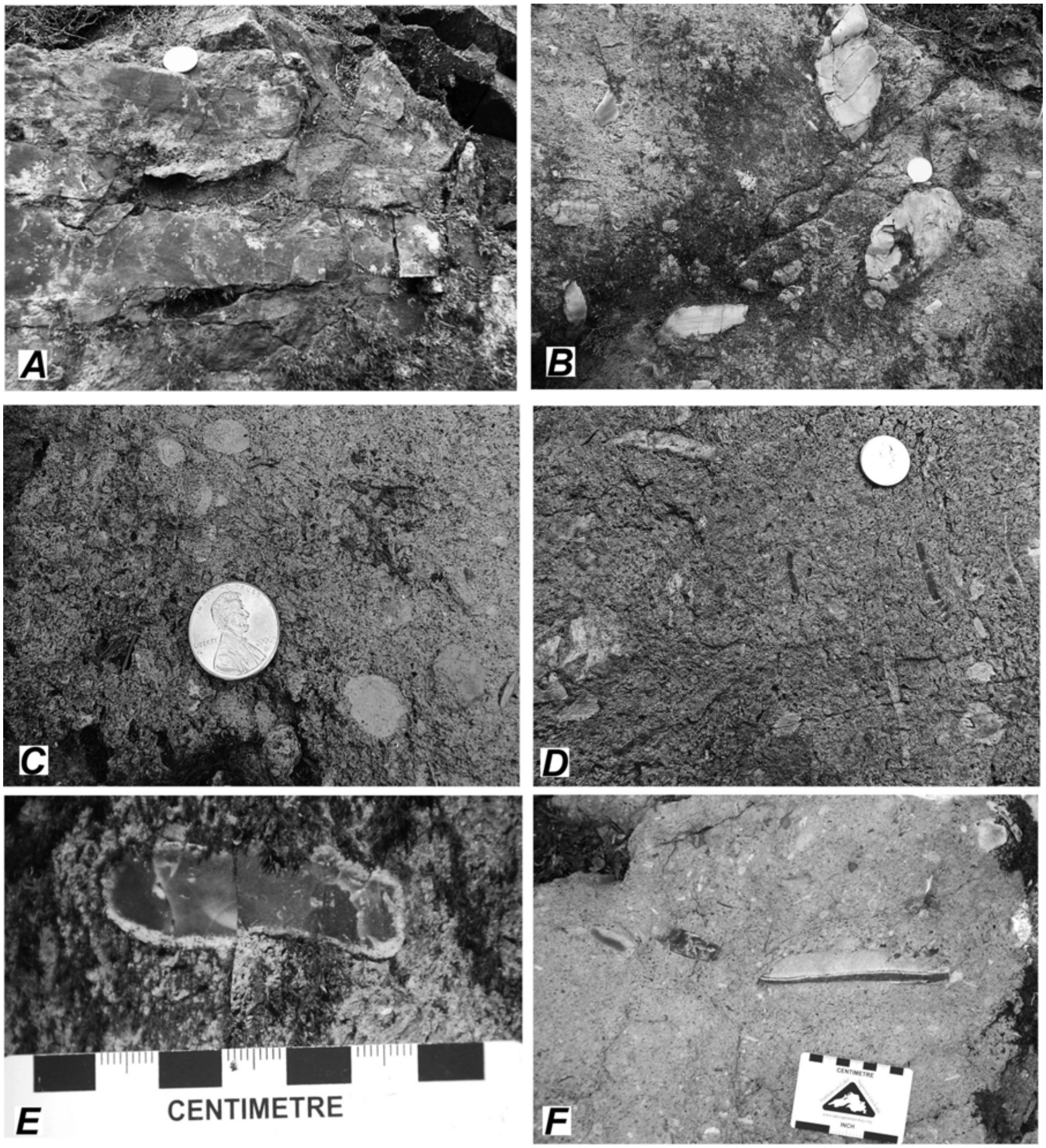

Figure 5.6. A- Coarse breccia at base of Sudbury layer containing meter-scale slabs of the inderlying iron formation.
B- Typical lower breccia containing chert fragments supported in a matrix of sand-sized quartz grains and fragments of altered glass.
C- Accretion lapilli in matrix of lower breccia.
D- Elongated chert fragments showing preferred orientation.
E- Chert fragment in lower breccia showing alteration rim.
F- Lower breccia with an unusually high abundance of exotic (non-chert fragments.
Coin is US penny in A-D.

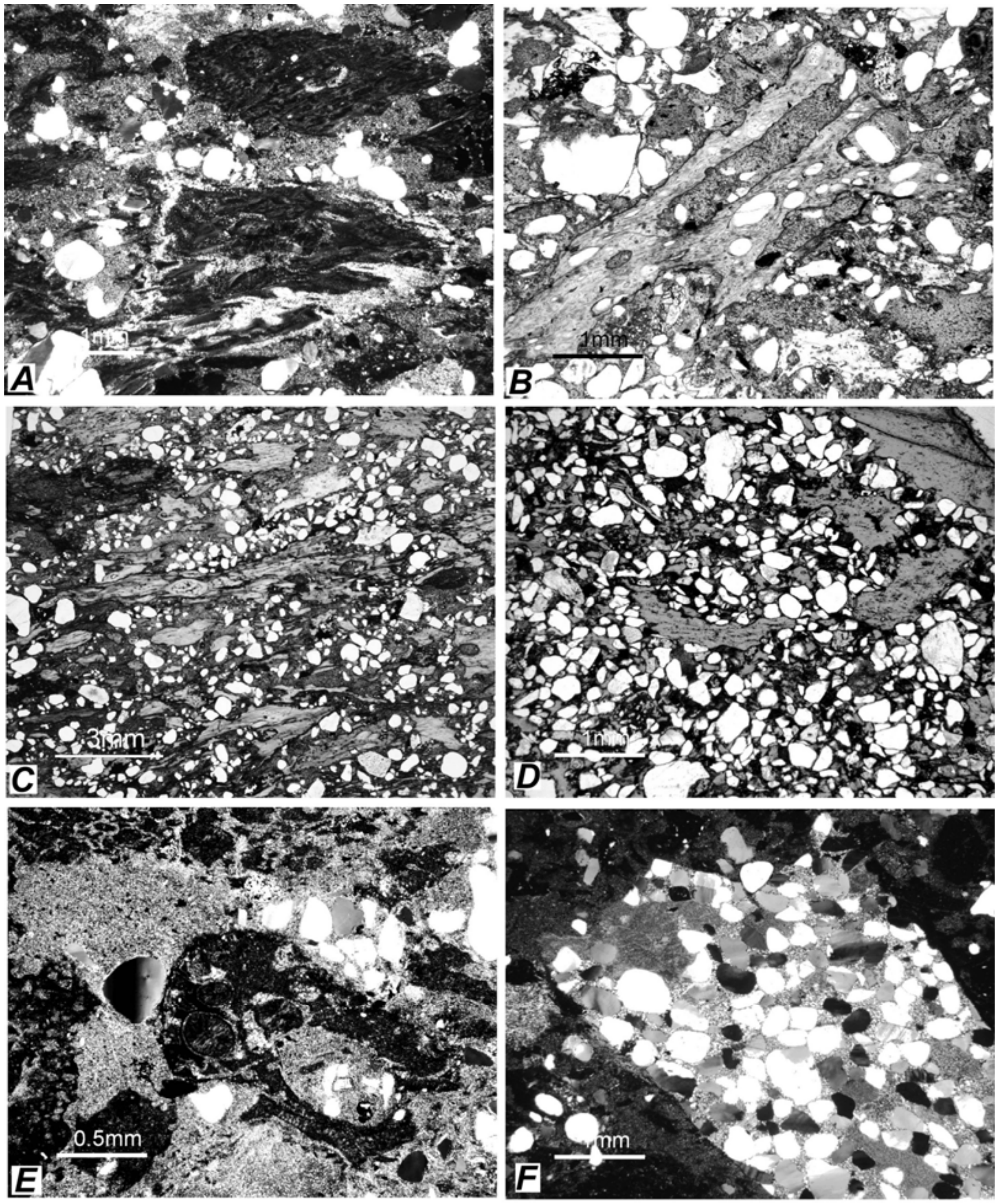

Figure 5.7. Photomicrographs of samples from the McClure site.
A-Complex glass particle from lower breccia with two distinct compositions, possible immiscible melts.
B- Complex fiamme of highly vesicular glass, now largely chlorite (trending upper right to lower left).
C- Lower breccia matrix with numerous flattened particles of vesicular glass, now largely chlorite.
D- Upper sandstone with numerous particles of altered glass, now largely chlorite;
E- Vesicular glass particle in lower breccia and aphanitic matrix.
F- Grain of quartzite in matrix of lower breccia.
Note the abundance of rounded quartz grains in all samples.

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54th Annual Institute on Lake Superior Geology

Field Trip 6

SUSTAINABLE RECOVERY OF IRON FROM THE MARQUETTE DISTRICT

Glenn Scott, Helene Lukey, Al Strandlie,
and CCI/CCMO staff

Cleveland Cliffs Inc.

Geology, Ore Processing and Reclamation at the Cleveland-Cliffs Michigan Iron Mines

Ishpeming, Michigan

54th Annual Meeting of the
Institute on Lake Superior Geology
May 10, 2008

Cleveland-Cliffs
MICHIGAN OPERATIONS

WELCOME

Welcome to Cleveland-Cliffs Michigan Operations!

In the early discussions of field trips for this conference, Ted Bornhorst suggested the inclusion of the processing plants in addition to the "standard" geologic tour. As we talked, this expanded into something with a decidedly broader scope to include a wide range of environmental quality and reclamation topics.

Therefore, in contrast to the Institute field trip in 1999, this excursion does not focus on the geologic details of the Negaunee iron formation and the ore. Instead, the attention will be on the mining, processing and associated environmental aspects through to closure.

Cleveland-Cliffs is proud of the environmental quality efforts at the Michigan Operations and we are looking forward to this opportunity to host the Institute.

Please remember safety at all times by wearing your protective equipment, watching for hazards and paying attention to the suggestions of the guides

We would like to thank Cleveland-Cliffs Inc and Cleveland-Cliffs Michigan Operations for supporting this visit. Special thanks to John Klasner for time and effort as editor.

Field guides are:

Helene Lukey
Al Strandlie
Al Koski
Keith Kramer
Karla Brudi
John Meier

Enjoy the tour – Glenn Scott

FIELD TRIP STOPS

NOTE: Unfortunately, CCI policy requests that visitors do not take photographs.

Empire Pit Service building

Pit operations for both the Empire and Tilden Mines are coordinated from the Empire pit service building.

Empire overlook - Al Strandlie

The view is to the north with the Empire Main Pit syncline plunging to the west. The CDV pit is to the northwest with the depleted CDI and CDII pits further north. Attachment 6-A

Hematite overlook - Helene Lukey

From the southwest end of the Tilden hematite pit, the mining operation and major geologic features can be seen (weather permitting).

The view is to the east with the fault contact between the iron formation and the Archean to the south, with the martite and carbonate ore operations below. The large hill to the northeast shows a cross section of the intrusives on the north limb of the anticline. To the north, the "Slot" leads along strike to CDIII and the magnetite deposit. Attachment 6-A

Ore Stockpiles

If the pit access is such that only drive by viewings of the ore sites are possible, samples of the primary ore types can obtained at the stockpile area.

Rock Stockpile reclamation - Al Koski

As part of the reclamation plan, the rock (waste) stockpiles are being vegetated on an ongoing basis. The results can be seen in several areas; time and access will determine the exact locations. Attachment 6-B

Tilden Plant - Keith Kramer

The processes are described in the Attachment 6-C. The plant metallurgists and operators will lead the tour.

Empire Tailings Basin - Gary Goodman

The rejected material from the concentrating process is pumped to the tailing storage basins. Construction, maintenance and water balance will be discussed by Cliffs personnel as illustrated in Attachment 6-D.

Access will be determined by weather and road conditions.

Republic Wetlands Preserve - John Meier

The Republic Wetlands Preserve is portion of Cleveland-Cliffs mitigation of impacts of the mining operations. The tour will be led by a representative of Cliffs Technology Group. The preserve is described in Attachment 6-E.

Access will be determined by weather and road conditions.

INTRODUCTION

Cleveland-Cliffs Inc has been active on the Marquette Range since 1847 and has operated a series of underground and surface mines. Production in the early years was of from high grade natural ores but since 1967 production has been from low grade iron formation as pellets. The Marquette Range production began in 1846 on natural ores and pellet production began in 1956 (Boyum, 1979). Total production of the now depleted natural ore was over 300 million tons and pellets exceed 500 million tons. Pellet production has come primarily from the now exhausted Humboldt and Republic Mines and the presently operating Empire and Tilden Properties.

On this tour, we will first visit the Empire and Tilden pits to observe the mining operations and examine the iron formation. We will then tour the Tilden concentrator and pellet plant followed with a visit to the active Empire tailings basin. Time and access permitting, we can view and discuss the reclamation of the rock stockpiles. The trip will conclude at the Republic Mine to view the reclaimed plant site and tailings area and to compare these to the active operations.

AS WE WILL BE IN OR AROUND ACTIVE WORKING AREAS, PLEASE BE AWARE OF MOBILE EQUIPMENT AND OF THE POSSIBLITY OF SLIPS AND TRIPS.

OVERVIEW

The Tilden and Empire Mines are operated by Cleveland Cliffs and are located in the Upper Peninsula of Michigan, about 30 kilometers from the shore of Lake Superior (Figure 6-1).

In the Lake Superior region, Tilden is unique in that the principle production (75%) is from a hematite deposit. The flotation process is complicated and can be sensitive to variations in mineralogy, chemistry and morphology of the iron and gangue minerals. The flotation ores are typically referred to as ‘hematite’. The actual minerals present and concentrated are hematite (both as martite and microplaty), magnetite, goethite/limonite and various carbonates including siderite, ankerite and dolomite. The common gangue minerals are quartz, chlorite and clays. Phosphorous occurs as apatite.

Magnetite mineralogy is simpler as nonmagnetic species are (mostly) rejected in the concentrating process. Gangue minerals are quartz, hematite and carbonates.

The 35% crude iron is upgraded to 65% before pelletizing. Annual production capacity is 8 million tons of pellets from 20 million tons of crude ore. Total production to date is 394 million tons of ore and 149 million pellet tons; published reserves are 717 million tons of ore and 260 million tons of pellets.

Empire processes only magnetite with a capacity of about 5 millions tons of pellets per year. Total production to date is 777 million tons of ore and 220 million tons of pellets.

Primary ore and waste parameters are crude to pellet weight recovery; concentrate chemistry (silica, phosphorous) and crude iron. These data are based on rather involved laboratory tests (Table 6-I) which may not directly reflect the plant response.

REGIONAL GEOLOGIC SETTING

The regional structures (Figure 6-2) are the Niagara Fault Zone, the collision zone between the Wisconsin Magmatic Terrane and the Superior craton (Schneider *et al*, 2002), and the Great Lakes Tectonic Zone, which forms the boundary between Archean granite-greenstone and gneissic terranes (Sims *et al*, 1980). In the Marquette Range area, deformation along the Great Lakes Tectonic Zone evolved from extension and deposition (Schneider *et al*, 2002) to closure and transpressional deformation and basin inversion (Cambray, 2002). The resulting fault-bounded shallow west plunging asymmetric syncline contains a series of second-order growth fault basins that define the detailed stratigraphic variations.

The Paleoproterozoic rocks in Michigan are termed the Marquette Range Supergroup (Cannon and Gair, 1970) and consist of three fining upward sequences (Map in Pocket). The lower portion has been correlated with the upper part of the Ontario Huronian (~2.2 Ga) and the upper parts, which contain the 1875 Ma iron formations, with the Mesabi Range of Minnesota. Simplistically, the sequence is from the Chocolay Group shelf facies quartzites and dolomite to the Menominee Group with argillites and the major iron formations to turbidites, greywacke and shale along with minor iron formation in the Baraga Group (Figure 6-3). Mafic igneous rocks with a continental tholeiite geochemical signature (Schulz, 1983) are present in the Menominee and Baraga Groups. Basal quartzites in each sequence are used as local structural and stratigraphic marker horizons. Metamorphic grades vary from sillimanite in the west to chlorite in the east and at the Tilden Mine (James, 1955)

Negaunee Iron Formation and equivalents hosted the majority of the natural ore deposits and all of the concentrating grade production in Michigan. In the Marquette trough, the Negaunee reaches a thickness of 1300 meters without including the mafic igneous horizons. Due to the lack of correlative iron formation horizons, the igneous rocks, termed sills locally, are used for structural markers. There appears to be a poorly defined change from dominantly carbonate-chert on the north to magnetite-hematite-chert on the south (Waggoner, 2007).

LOCAL GEOLOGY

The Tilden and Empire Mines are located on the southern margin of the trough and are in fault contact with the Archean gneiss terrane (Attachment 6-A, Figure 6-3and 6-4). Local structure consists of upright to steeply inclined second order anticlines and synclines with low angle northwest and southwest plunges (Cambray 2002, Webster, 1999). At Tilden, due to the lack of clear marker horizons and rapid facies changes within the iron formation, igneous horizons are used for stratigraphic and structural correlation (Lukey, Johnson and Scott, 2007). At Empire, stratigraphy is determined by the igneous horizons and by the proportions of carbonates, silicates and clastics in the iron formation (Nordstrom, 1997; Han, 1975). See Figures 6-4 through 6-9 for mine geology.

GEOLOGIC DOMAINS

The domains are defined by geologic and metallurgical consistency (Table II, III) and are the basis for the resource modeling (Scott and Lukey, 1999; Nordstrom, 1999).

Magnetite deposits are less variable (or perhaps the process is more forgiving). As there is no type example of iron formation within the mine, it is problematic if the mineralogic and textural variations reflect deposition in growth fault basins, diagenesis or hypogene events.

IGNEOUS ROCKS

Two ages of mafic rocks occur in the mine, the synsedimentary sills and associated dikes and a dike series of Keweenawan (~1000 Ma) related to the Midcontinent Rift. The older series vary from fine porphyritic to diabasic/ophitic and typically display chlorite-carbonate alteration assemblages, particularly in deformation zones. The younger series are typically unaltered diabase.

The iron formation is variably altered along the intrusive contacts with the type and extent of alteration dependent on the thickness of the intrusive and the composition of the iron formation.

FOLDING/FAULTING

The major structures are the large (100s meters) scale Tilden Main pit anticline and Empire Main pit syncline; the fault that marks the contact of the Southern Complex and the iron formation; and the CDIII syncline. Smaller features (Figure 6-4) are the Section 20, CDI, II and V mining areas. Present geometry of these features is related to transpression during basin closure (Webster, 1999). The fault, initially a basin margin listric normal fault, was reactivated and is now a reverse fault that dips about 65° north (Cambray, 2002). At blast pattern level, faults and folds at the 1-20 meter scale tend to follow the trends seen in the larger structures. These features, while of relatively small amplitudes, can be significant in the detail block modeling and ore type boundaries.

MINING AND PROCESSING

The mining, concentrating and pelletizing processes are described in some detail in Attachment 6-B. The sequence begins with a scheduled mine plan and blast design. Holes are drilled, sampled and blasted. Broken ore is loaded into trucks to be transported to either the crusher and waste is taken to a rock stockpile.

After initial crushing, the ore enters a series of autogeneous mills where it is ground to ~80% -31 microns (face powder) before the iron minerals are separated from the gangue. The magnetite process relies primarily on mechanical separation using the magnetic properties of the minerals. Hematite is processed by flotation and relies on chemical reagent selectivity. The tailings are pumped to the tailings basins and the water returned to the process (Attachment 6-D).

Pelletizing is essentially the same in either ore type. The concentrate is “rolled’ into “green balls’ which are fired in the kilns to harden them for shipment. The kilns are heated by a combination of coal and natural gas.

ENVIRONENTAL QUALITY AND RECLAMATION

During operations, discharges of materials that might be harmful to the environment are monitored and prevented. This includes discharges into the water and air such as trace chemicals and particulate matter from stacks, tailings and roads.

As stockpiles are completed the reclamation process is begun with introduced vegetation (Koski, 2007, Attachment 6-B). An example of closure reclamation will be seen at Republic Mine (Attachment 6-E).

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Table 6- I

Glossary of Terms and abbreviations used at the mine and plant

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 (i.e., the head Fe). The formula used for this calculation is called the iron balance formula, or sometimes called the concentration formula.

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

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 ($Fe2O3$), magnetite ($Fe3O4$), goethite ($Fe2O3*OF$) and iron carbonate ($FeCO3$).

Concentrate Silica Grade - The chemical measurement (assay) of the % $SiO2$ 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. Recovery, at some iron grade, with the head Fe of the crude. For example,

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

Percent Magnetic Iron Recovery (% 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) o the crude ore. For example,

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

Tailings - The product lost in the process. Tailings always include iron, because iron is always associated with many other minerals (silica, phosphate, carbonate, etc. or may be a liberation issue).

Flot (flotation) – Flot ores are the martite, hematite, goethite, clastics 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).

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

The assumption is that all of this occurs as magnetite. However, in the Tilden ores an appreciable amount of hematite is locked up 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 overestimate the 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 material with similar metallurgical response. These are usually stratigraphic horizons but may be fault bounded or nonconformable alteration/oxidation zones. The domains are the basis of the economic and planning models.

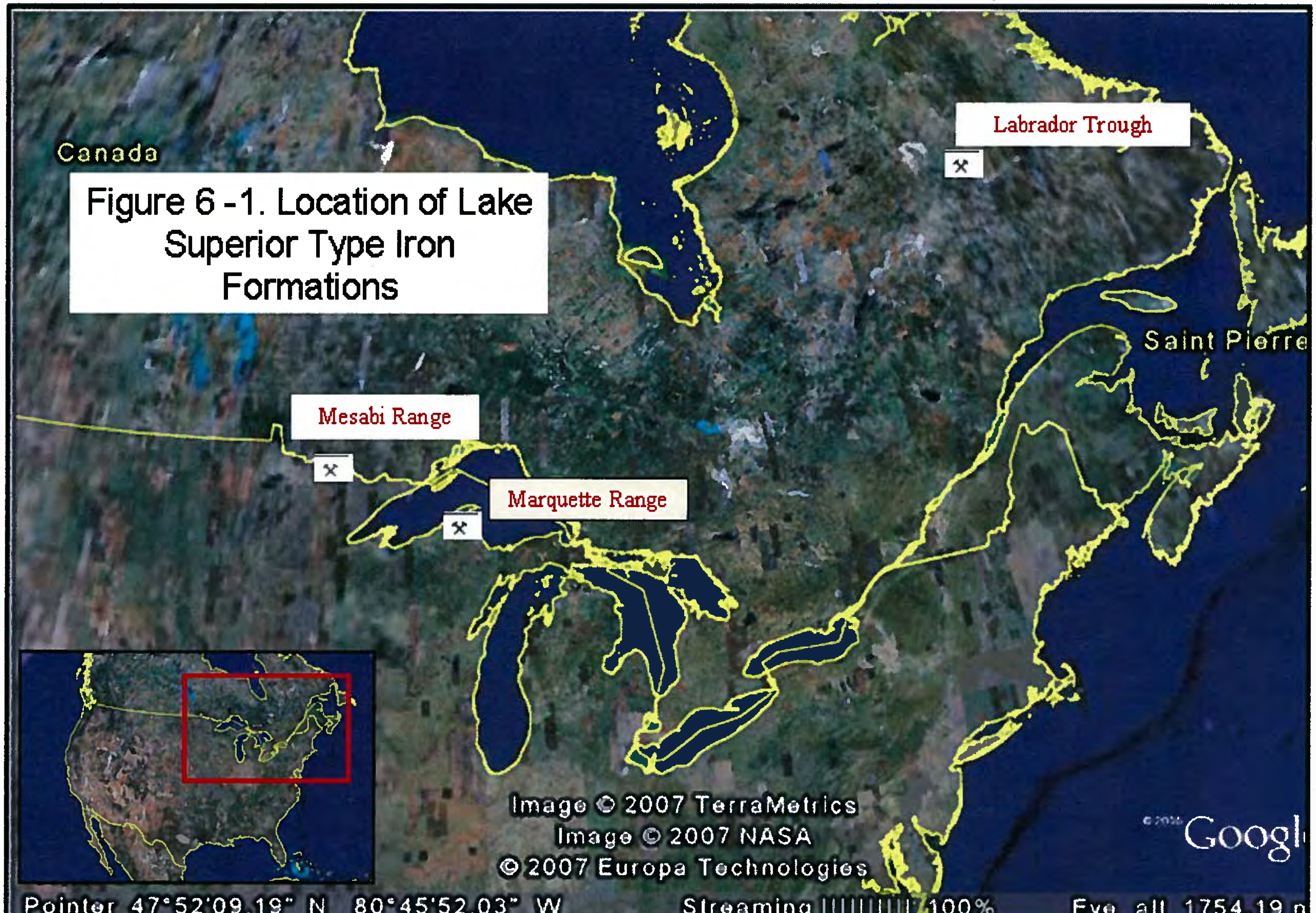

Figure 6 -1. Location of Lake Superior Type Iron Formations

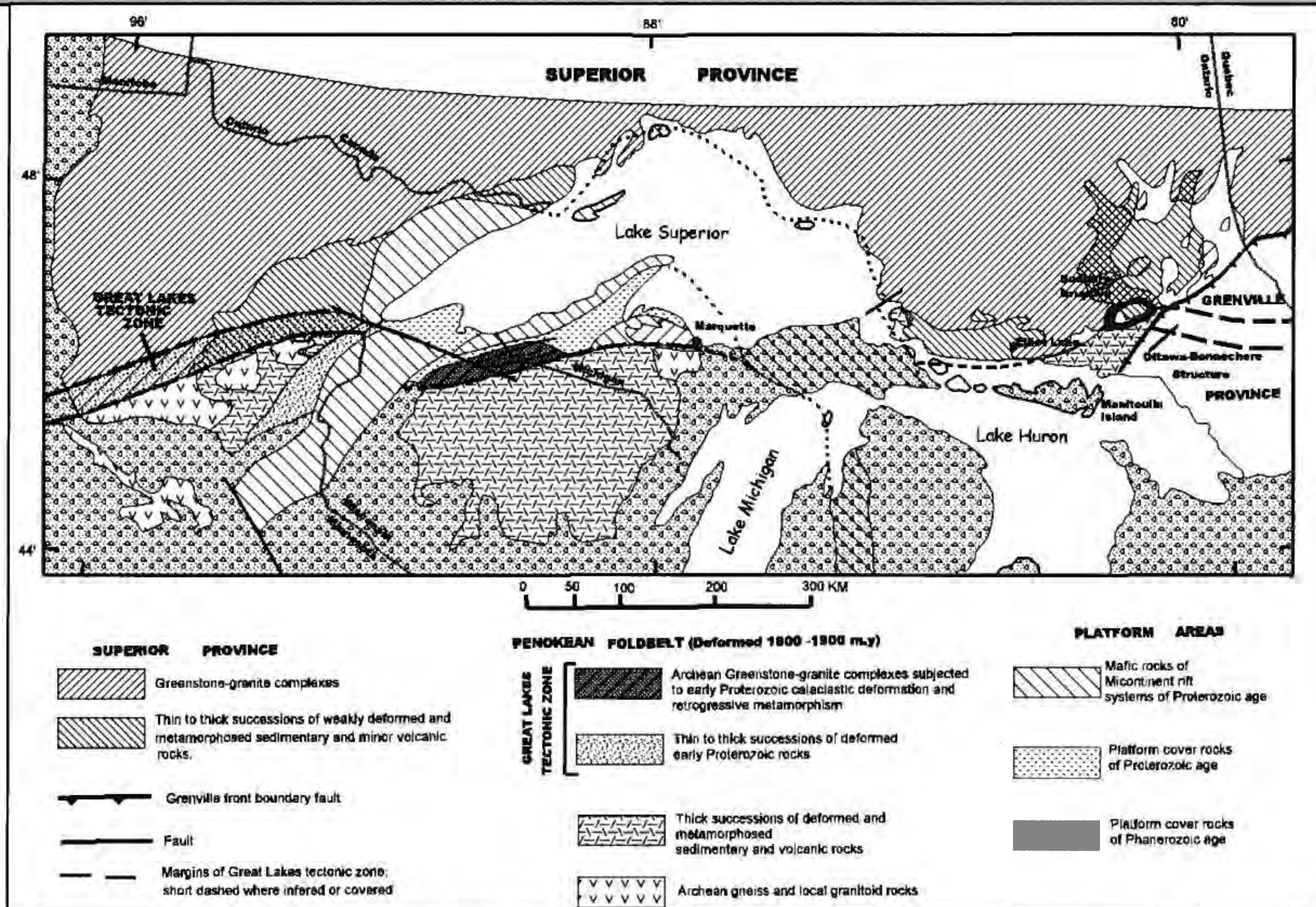

Figure 6-2. Simplified Geologic Map of Great Lakes (Modified from Sims *et al* 1980)

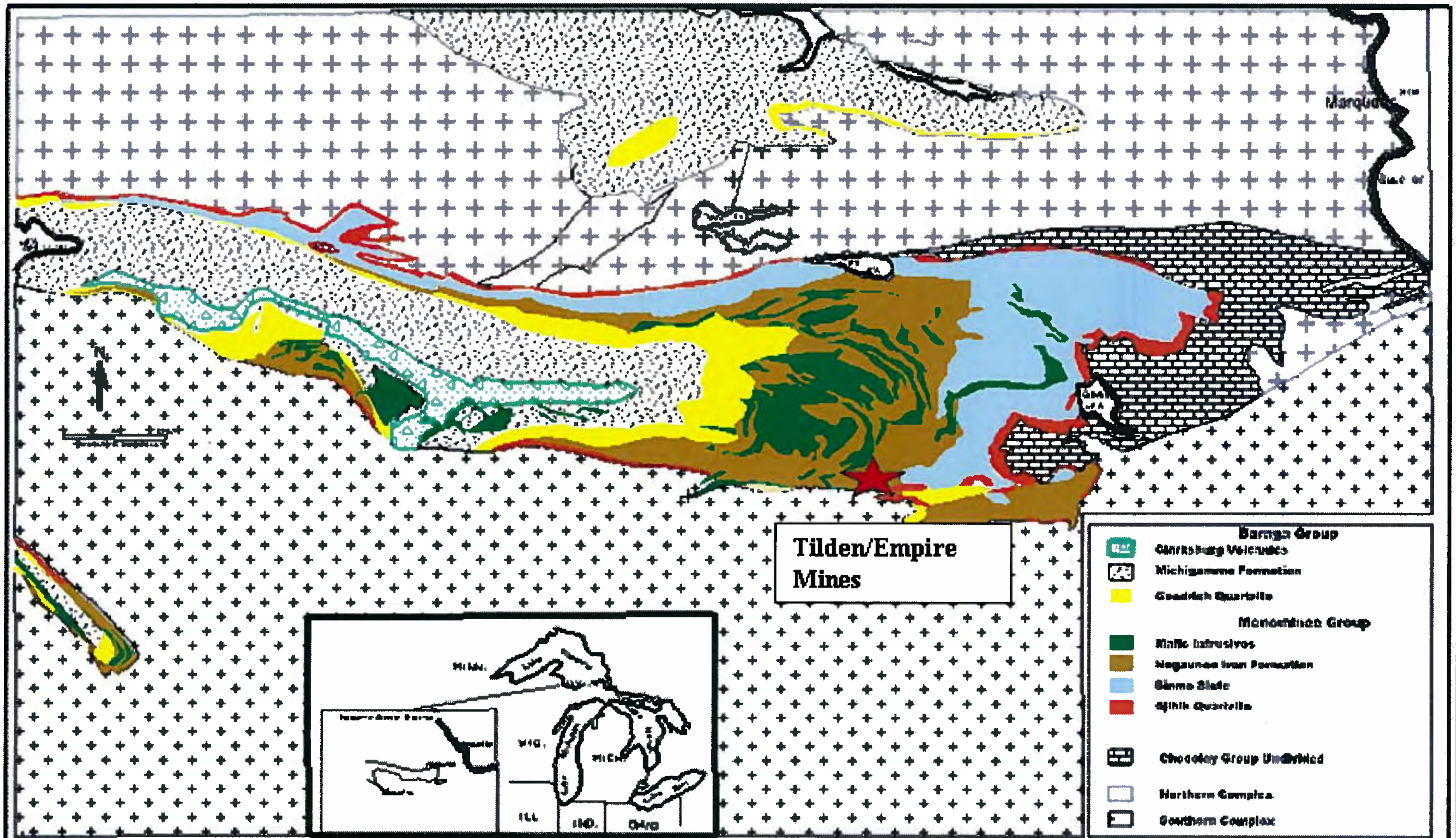

Figure 6-3. Generalized Geology of the Marquette Range Supergroup and Location of Tilden Mine.

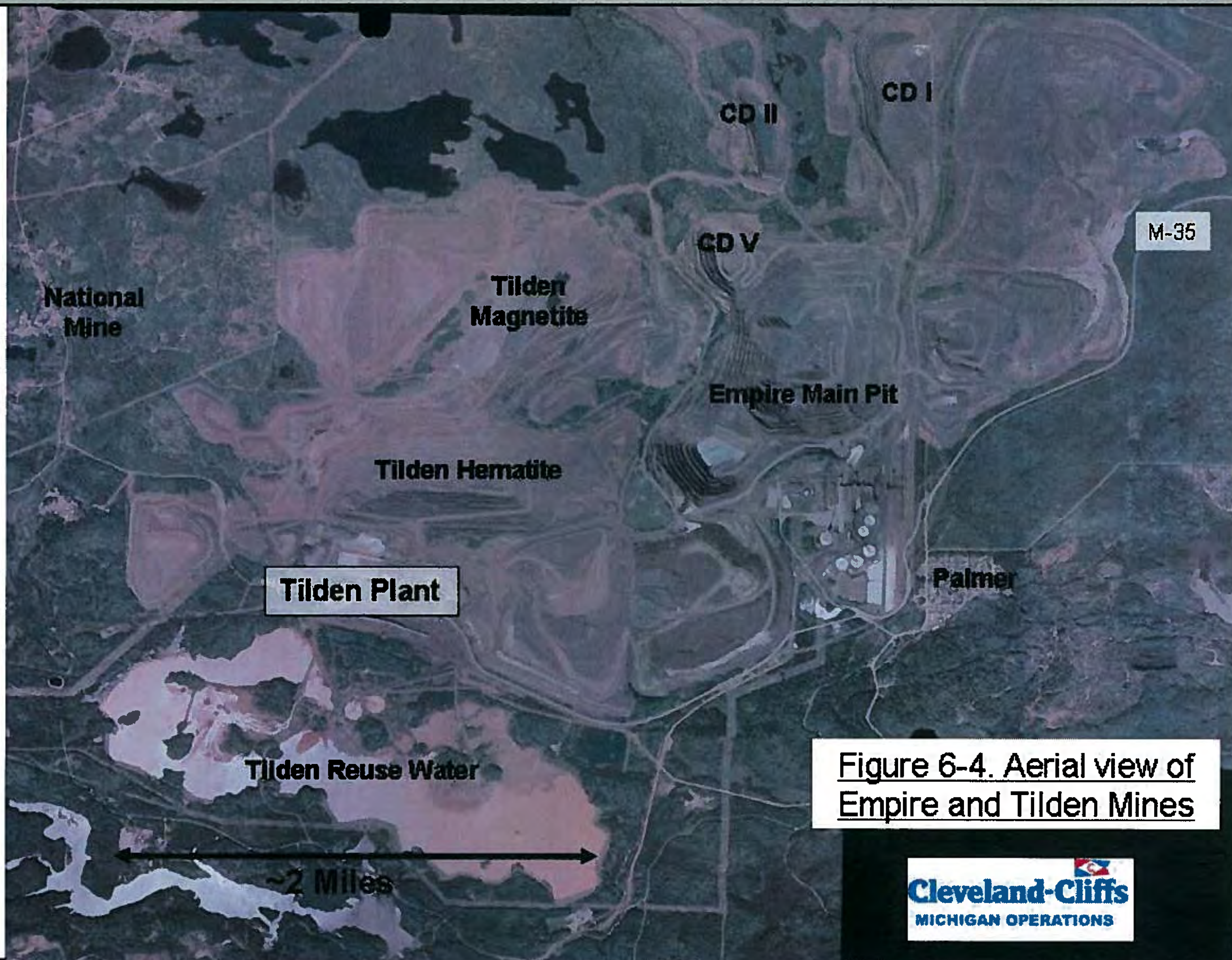

Figure 6-4. Aerial view of Empire and Tilden Mines

Attachment 6-A

Geology

Regional and Mine Area

Helene Lukey, CTG Geology and
Al Strandlie, CCMO Mine Engineering

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CD V
Main Pit
Empire Mine – Palmer, Michigan
Cleveland-Cliffs Michigan Operations

Table 6-II
Geologic Domains- Empire
from Nordstrom , 1999

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.

(Fig.6-5,6)

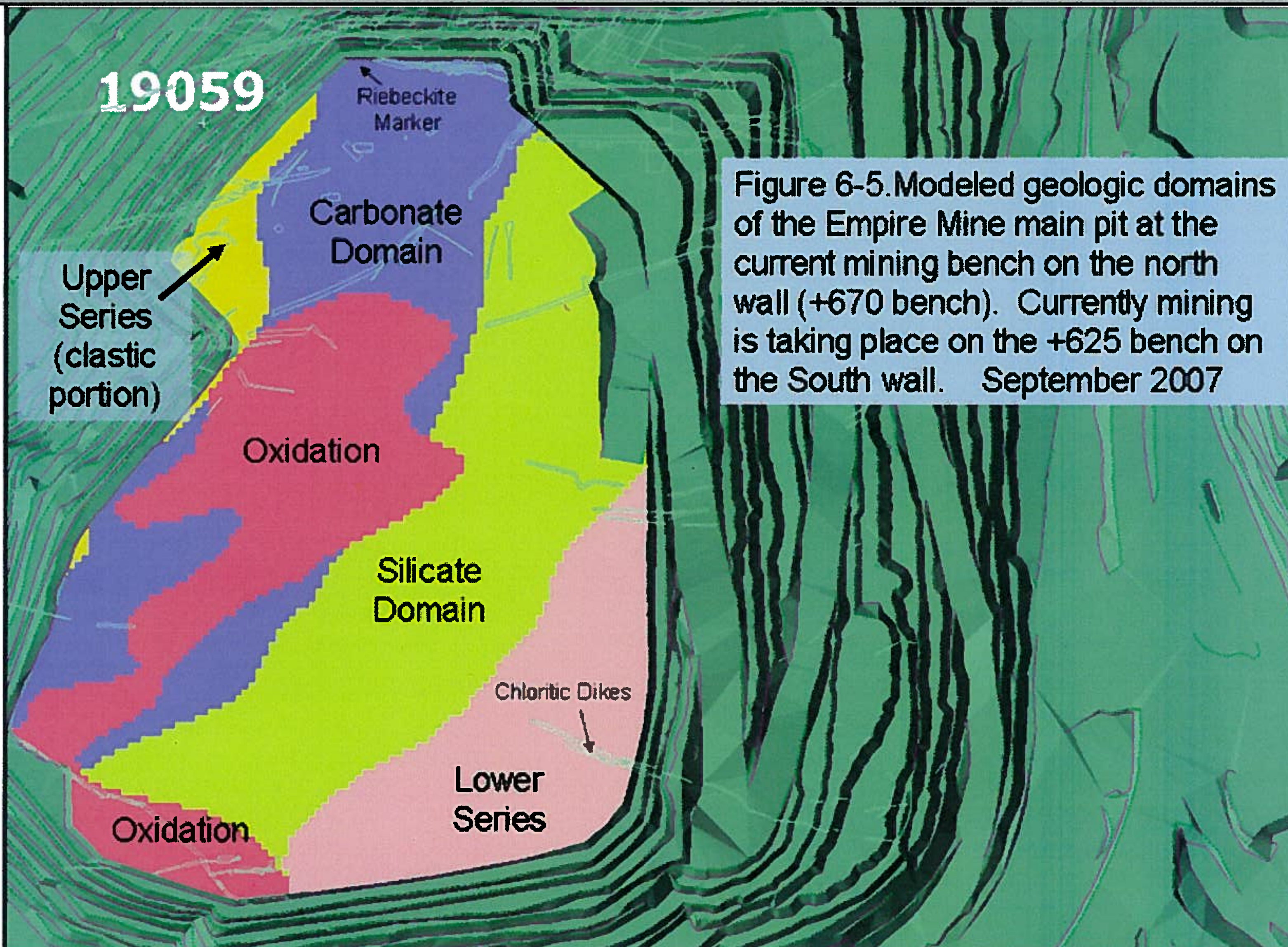


Figure 6-5. Modeled geologic domains of the Empire Mine main pit at the current mining bench on the north wall (+670 bench). Currently mining is taking place on the +625 bench on the South wall. September 2007

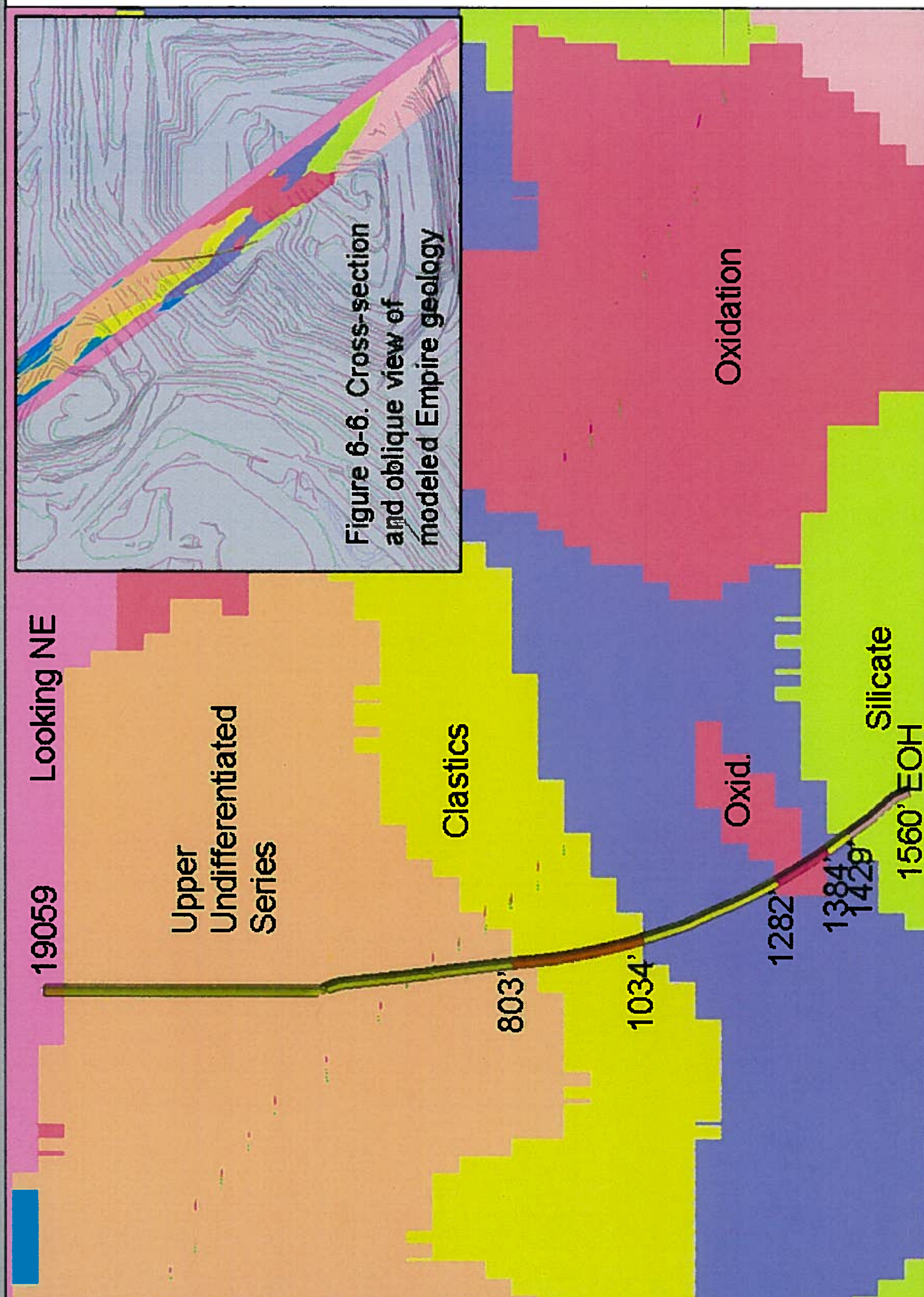


Figure 6-6. Cross-section and oblique view of modeled Empire geology

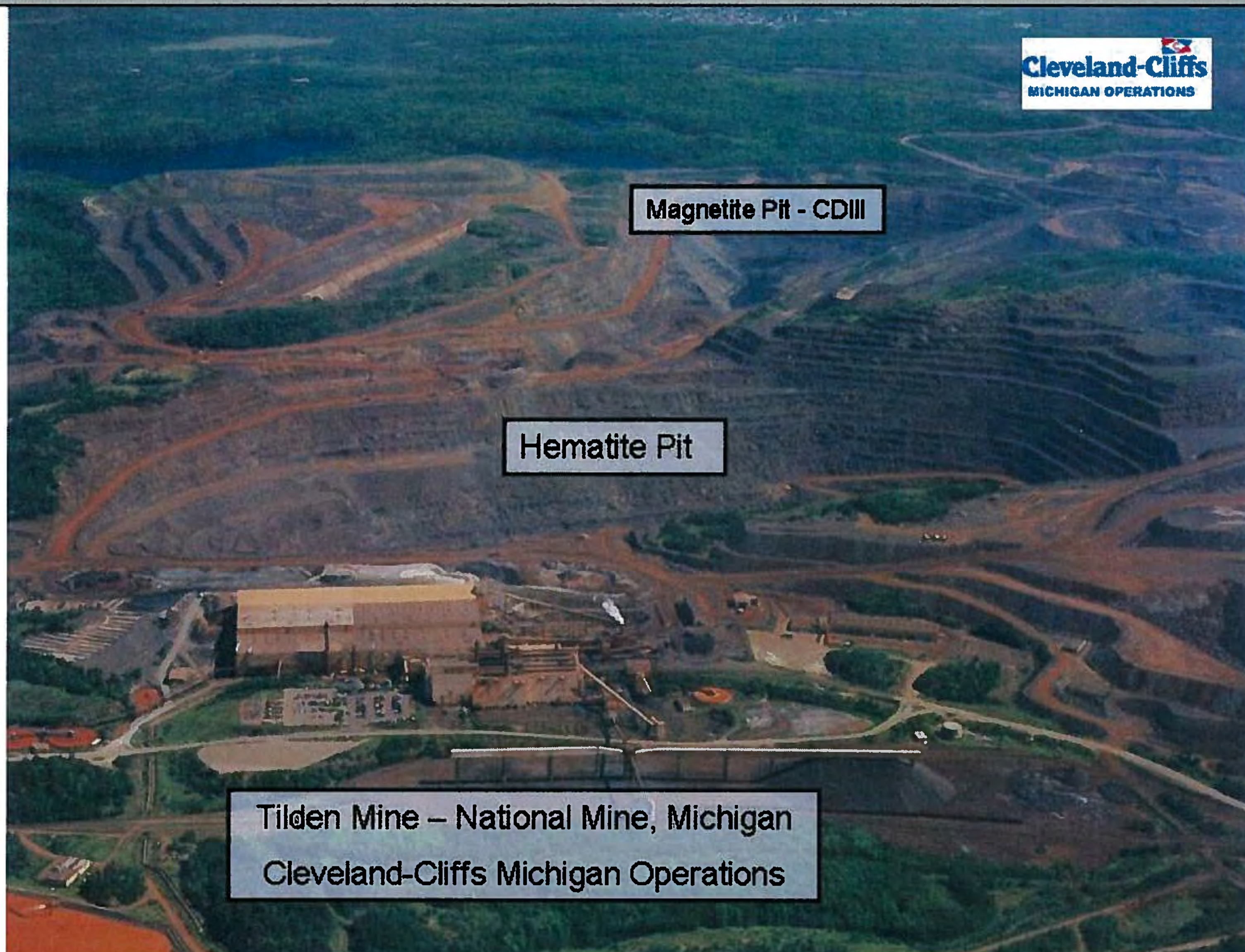

Cleveland-Cliffs
MICHIGAN OPERATIONS
Magnetite Pit - CDIII
Hematite Pit
Tilden Mine – National Mine, Michigan
Cleveland-Cliffs Michigan Operations

Table III

GEOLOGIC DOMAINS - TILDEN MINE

500 NORTHWEST DOMAIN

Stratigraphically above *CDIII/West pit hanging wall metadiabase* (250) and below *North Intrusive* (270); includes numerous dikes and one mappable igneous horizon, the *West Intrusive* (260).

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

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

531 dominantly goethite-chert with wt rec low 30-mid 40; variable, but generally high, silica and phos.

532 oxidized martite/goethite; low wt rec, high silica and phos; low heads indicate original iron formation may have been carbonate(?). Sulfates locally common in bench faces.

520 *Magnetite domain* dominantly magnetite-carbonate with silicate horizons. Flot and/or mag ore in part depending on liberation.

510 *Clastic horizon* at contact with top of the *CDIII/West pit hangingwall* (250) in local (?) syncline. Flot ore in part.

400 CDIII-WEST PIT DOMAIN

Stratigraphically between *CDIII/West pit hanging wall metadiabase* (250) and *CDIII footwall* (230). Includes numerous small dikes and sills, the Keweenawan 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. The dikes result in a high dilution factor.

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

451 *Goethite zones* within hematite domain. Associated with folding and faulting.

452 *Goethite zone along CDIII footwall*, south of Keweenawan dike. Typically high slime Fe, may be oxidized C*arbonate* (430) domain along intersection of dike and footwall.

440 *North hematite domain* consists of fine grained oxidized martite-hematite chert with numerous dikes. 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 wt rec and low concentrate grade. Fault bounded on north and south but apparently gradational down dip to west to *magnetite domain* (420).

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

421 *West pit magnetite domain* is an isolated zone of high grade magnetite and flot carbonate in west pit. Defined by drilling and blast pattern data.

422 *Magnetite-carbonate* - restricted flot domain near the top of and gradational with the 420 and 450 domains.

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

300 MAIN PIT DOMAIN

Contains iron formation units stratigraphically below the *CDIII footwall metadiabase* (230) and/or the *East pit hangingwall metadiabase* (200). 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 hangingwall* (200). 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. Includes horizons of magnetite-carbonate iron formation and thin dikes.

Gradational transition over 20-50 feet

340 *Carbonate iron formation* stratigraphically below the *hematite-martite domain* (350) in East pit. Consists of martite-carbonate-chert with variable magnetite/martite content. Defined by magnetic Fe, weight recovery and total oxides. Has lower weight recovery and higher concentrate grade than CDIII carbonates (430). 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. Does not differentiate nonliberating hematite material. May be stratigraphically controlled. Includes some flot ore within boundaries.

320 *East pit clastics* are mixed siliceous and silicate clastics and hematite iron formation. Includes oxide and carbonate horizons. A thin dike defines the north boundary, presumably marking a fault, with the *martite* or *carbonate domains*.

321 High silica zones (6 to >10%) in *clastic domain* reflects clay and/or Fe-silicates and/or nonliberating iron formation.

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

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

200 INTRUSIVE DOMAINS

These domains are used for correlations of the iron formation domains, and structural trends, and appear to be conformable at the scale of the ore body. Generally interpreted as intrusives, they consist of mafic rocks, which vary from diabasic to porphyritic to aphanitic. All units 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 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 The *CDIII/West pit hangingwall* is a relatively easily mappable horizon and along with the *CDIII footwall* (230) is one of the principle stratigraphic correlations between the CDIII pit and the Main pit.

240 The *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 The 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. Includes east-west trending 30+ foot thick Keweenawan dike in CDIII.

200 The *East pit hangingwall is* separated from the *CDIII footwall* (230) by the *Transition zone* (360) iron formation. 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 that 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 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

Quaternary overburden, rock fill and broken bench material

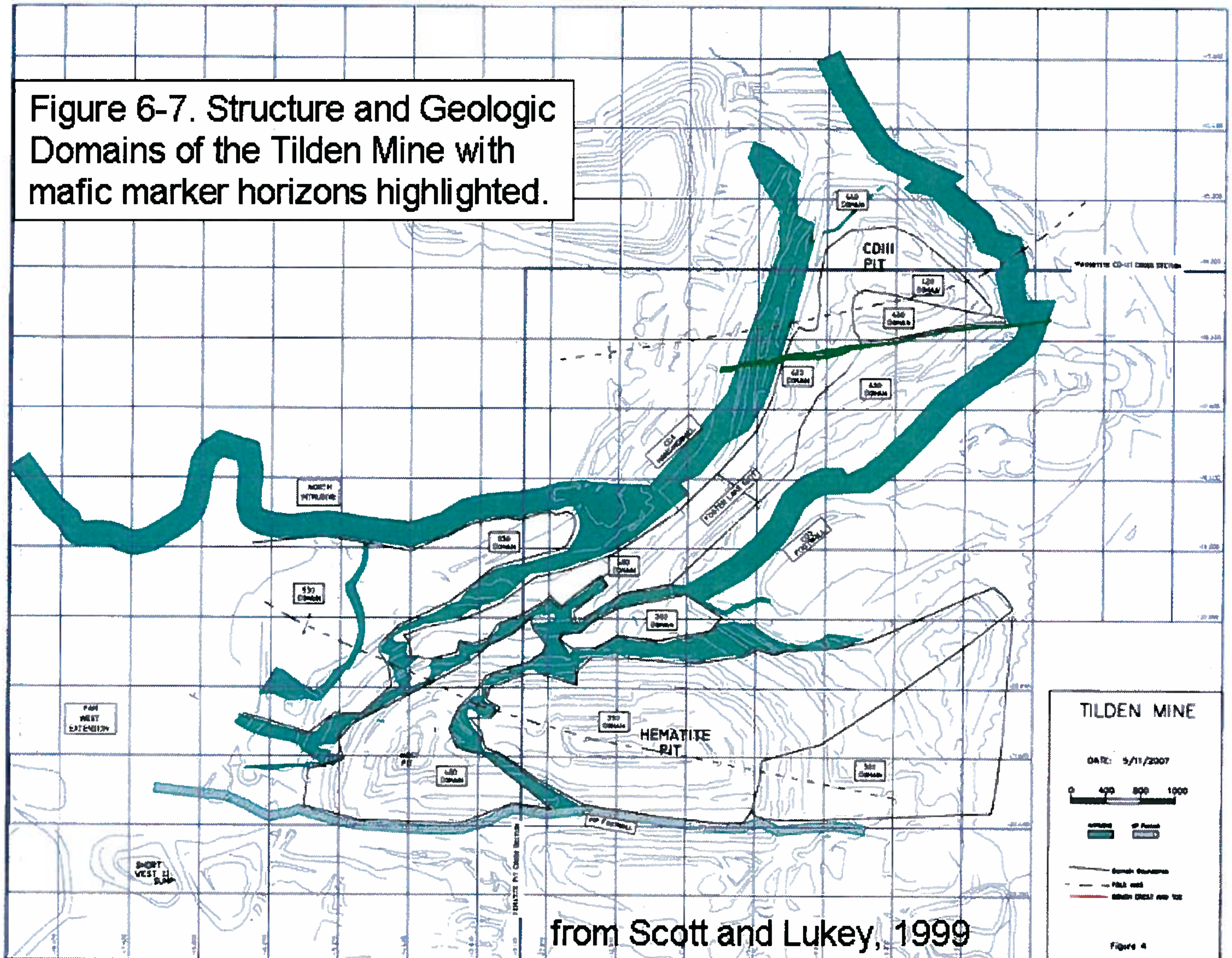


Figure 6-7. Structure and Geologic Domains of the Tilden Mine with mafic marker horizons highlighted.

from Scott and Lukey, 1999

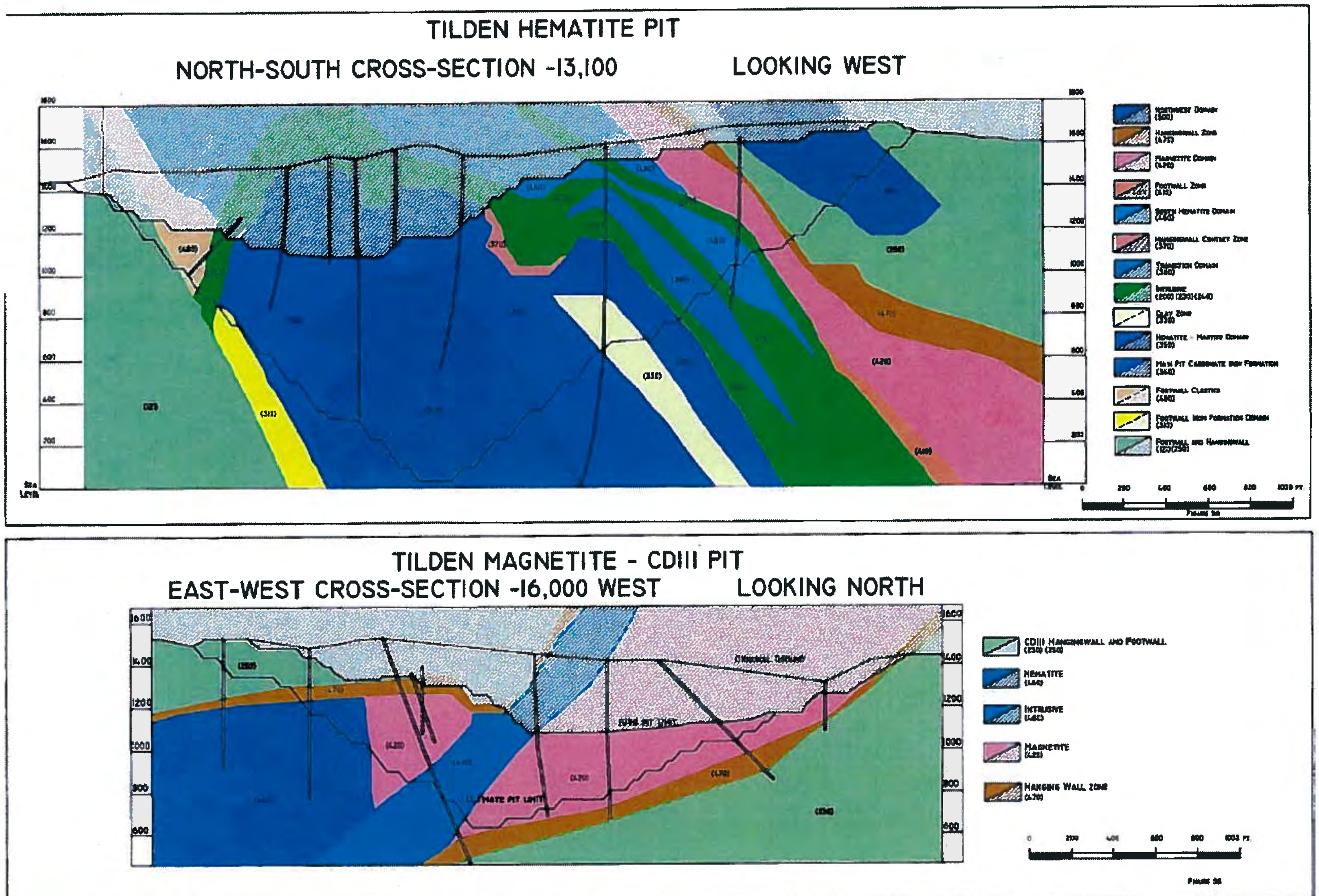

TILDEN HEMATITE PIT
NORTH-SOUTH CROSS-SECTION -13,100
LOOKING WEST
TILDEN MAGNETITE - CDIII PIT
EAST-WEST CROSS-SECTION -16,000 WEST
LOOKING NORTH
CDIII HANGINGWALL AND FOOTWALL
HEMATITE
INTRUSIVE
MAGNETITE
HANGING WALL ZONE

Figure 6-8

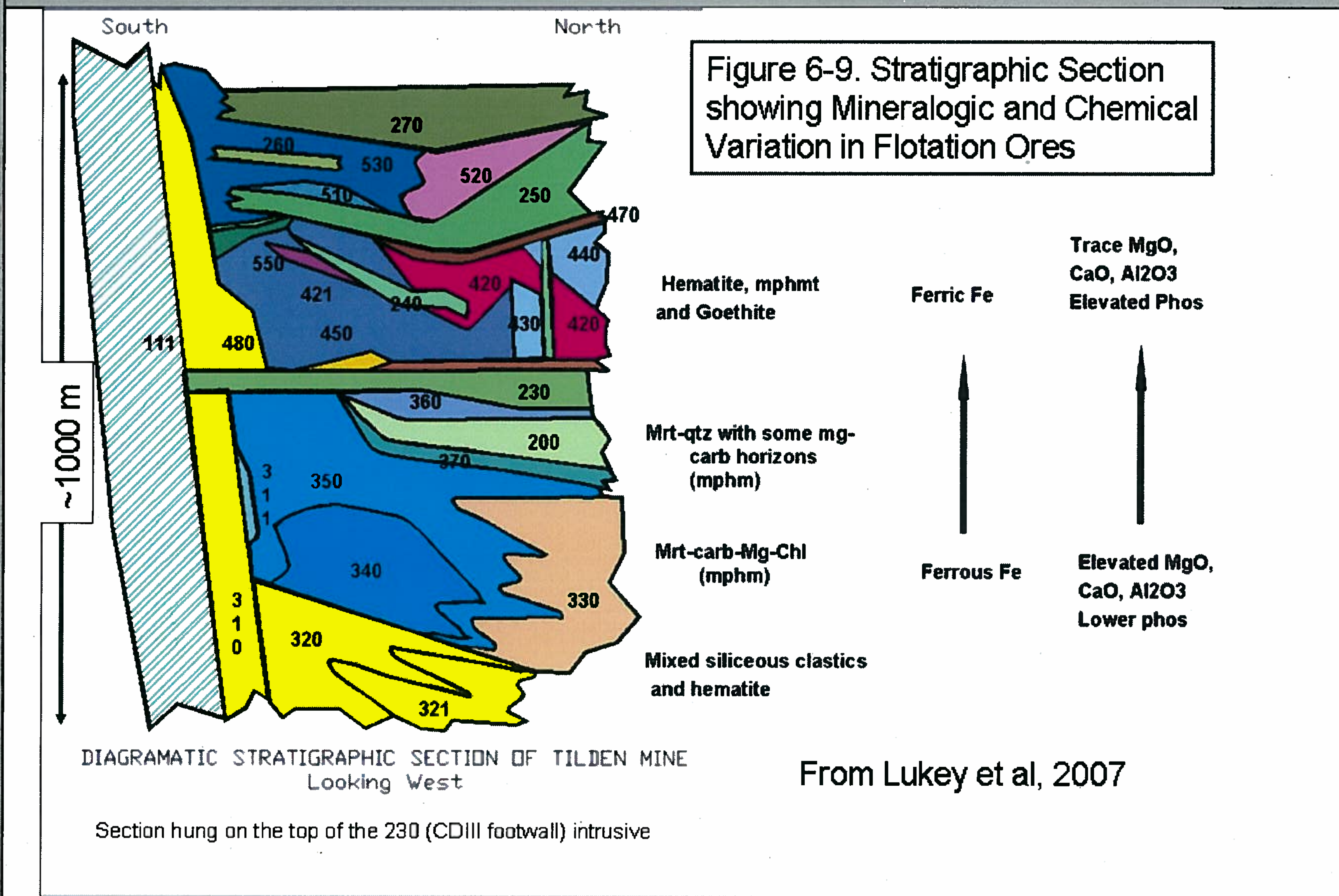


Figure 6-9. Stratigraphic Section showing Mineralogic and Chemical Variation in Flotation Ores

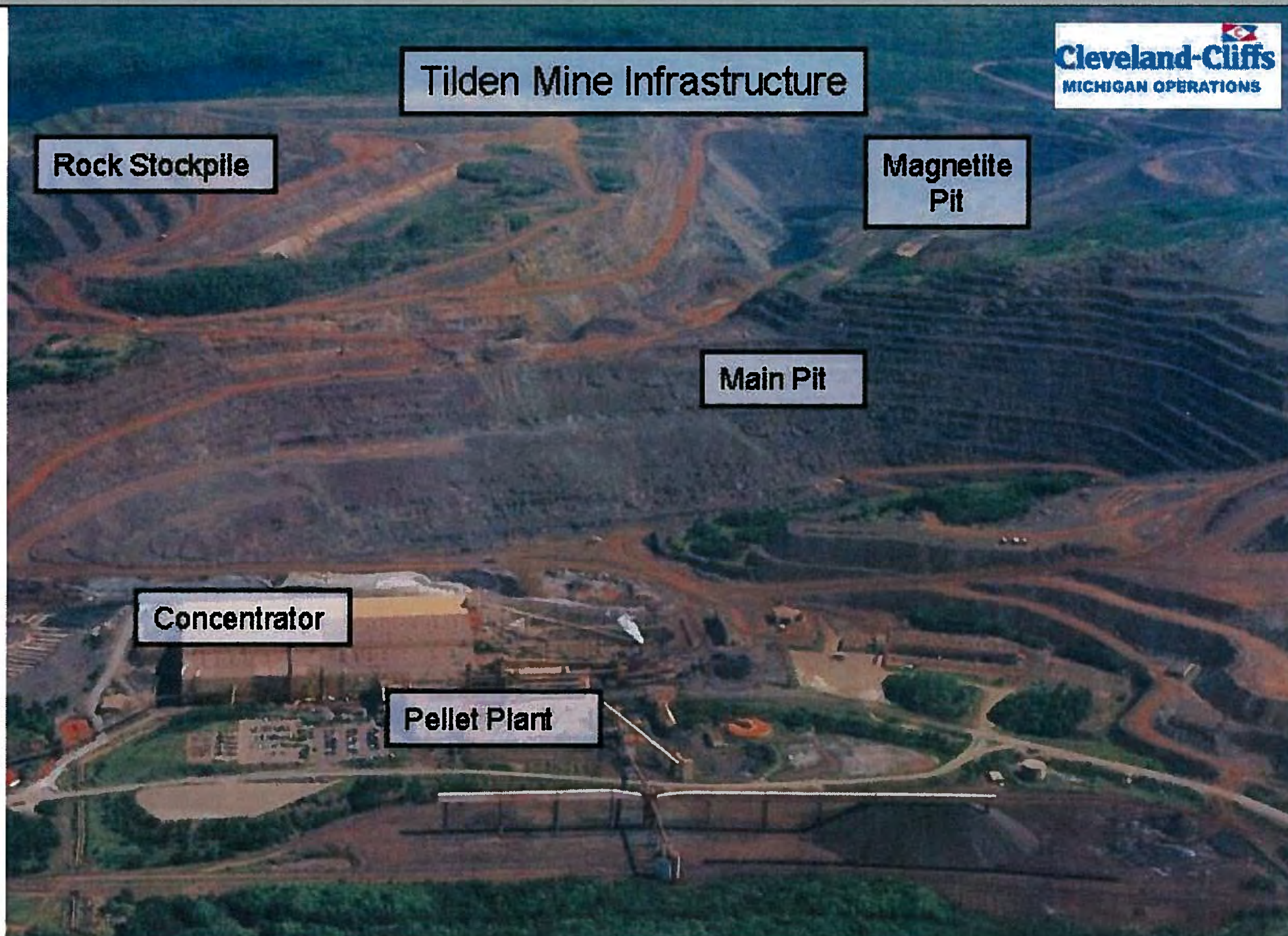
Attachment 6-C

Mining and Processing

Pit Operations, Concentrating and Pelletizing

Keith Kramer, CTG Process Metallurgist

Cleveland-Cliffs
MICHIGAN OPERATIONS

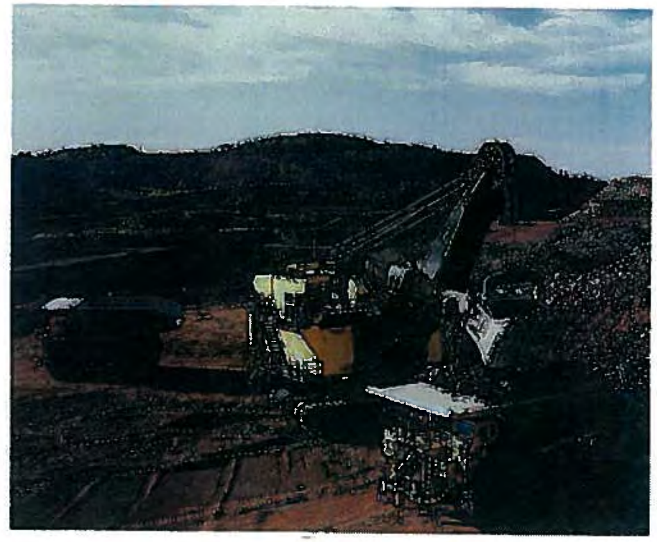

Tilden Mine Infrastructure
Cleveland-Cliffs
MICHIGAN OPERATIONS
Rock Stockpile
Magnetite Pit
Main Pit
Concentrator
Pellet Plant

Mining Operations

The mining operation is the same in either open pit. Rotary drills (above) drill 16-inch holes 50 feet deep in precisely laid-out patterns, which can include as few as 30 or as many as several hundred holes. They are filled with explosives and set off in a carefully controlled blast, which breaks up the material for mining.

Electric shovels load the broken material into trucks (above right) for transport from the pit. Pit equipment includes shovels with 38-cubic-yard buckets and 170, 190 and 240-ton production trucks.

The crude ore is hauled to the primary gyratory crusher (right) where it is reduced to chunks less than 10 inches in size. From the crusher, the ore is conveyed to a covered ore storage building.



Mining

Millions of tons of material are mined each year to produce pellets at capacity levels. Some is rock and overburden which must be removed to gain access to the iron bearing minerals. This process is known in the industry as stripping.

The life-of-mine stripping ratio is about three-fourths to one. That means that three-fourths of a ton of rock must be removed to gain access to every ton of ore.

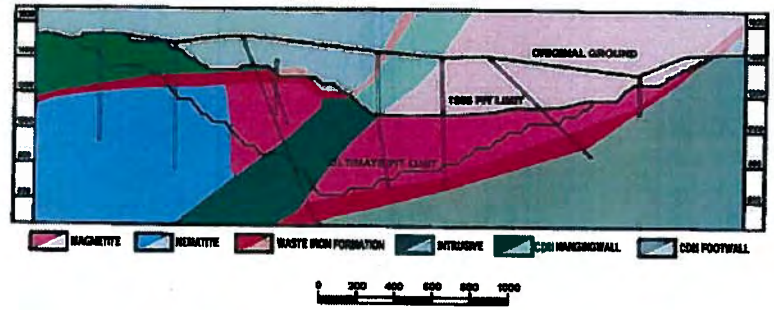
Since the ore is about 35 percent iron, three tons of iron bearing material must be mined for every ton of pellets produced.

To produce 7.8 million tons of pellets, for example, Tilden must mine about 36 million tons of ore and rock combined.

Tilden can mine either reserve, but it cannot process hematite and magnetite simultaneously. The production from each area in a given year will depend on owner and customer requirements.

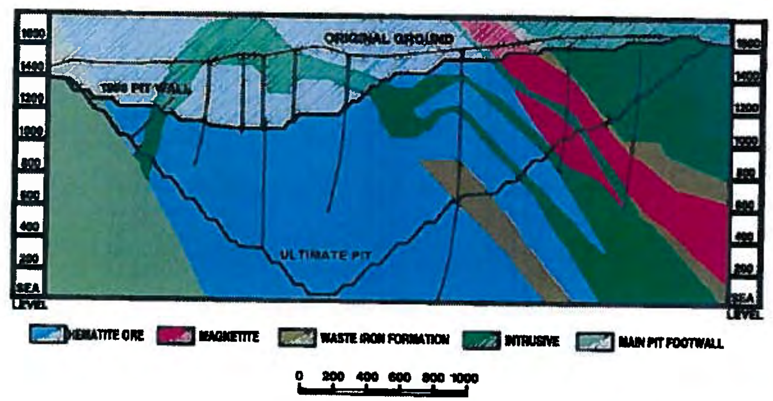
TILDEN MAGNETITE — CDIII PIT

EAST-WEST CROSS-SECTION -16,000 WEST LOOKING NORTH



TILDEN HEMATITE PIT

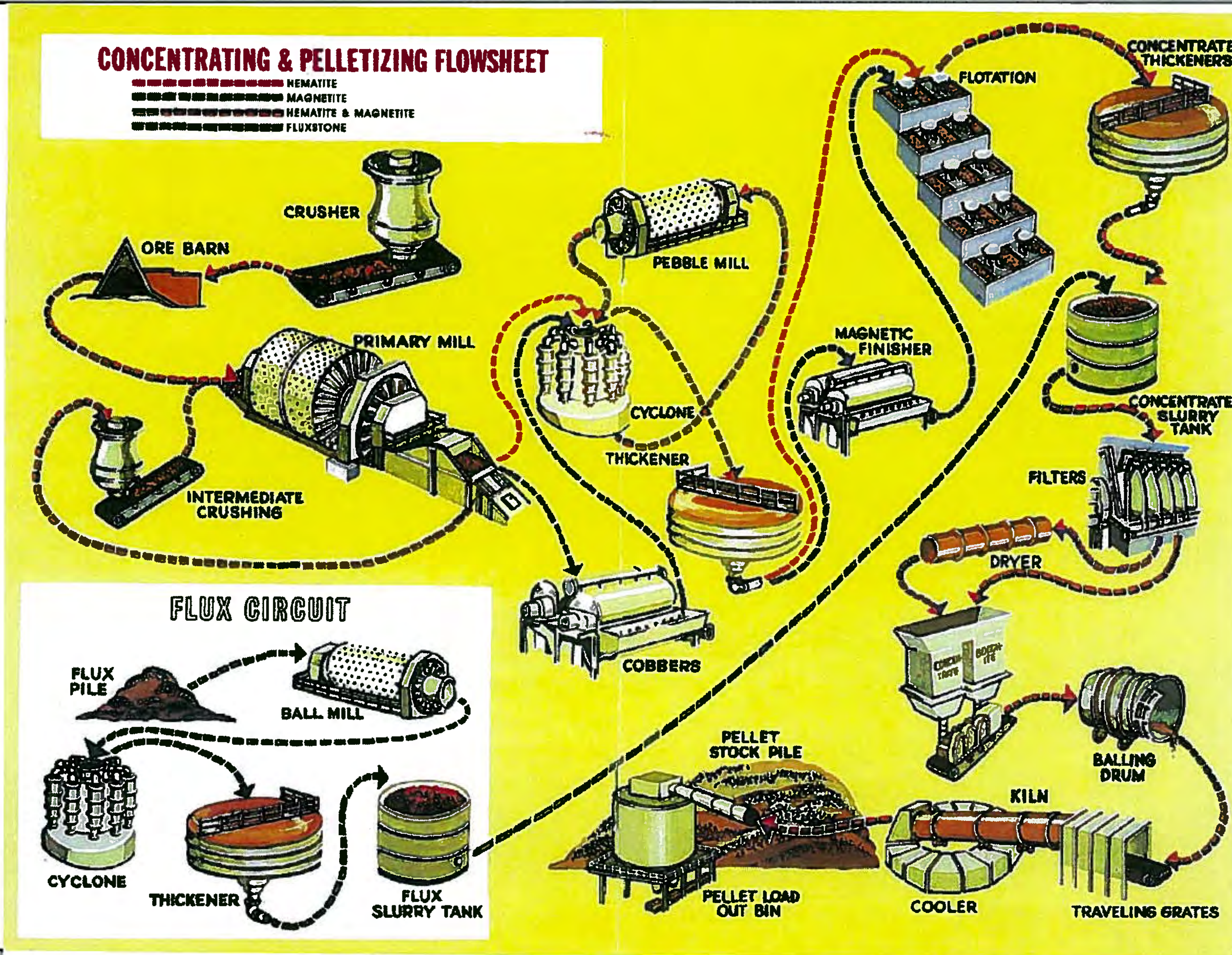
NORTH-SOUTH CROSS-SECTION LOOKING WEST -13,100 WEST



Processing

Turning crude ore into pellets occurs in the mine's concentrator and pellet plant. During concentrating, there are some steps which are identical and others which are unique to hematite or magnetite. The process in the pellet plant is the same for either type of ore.

A review of the simplified flow sheet on pages 11 and 12 describes the movement of material through the process.

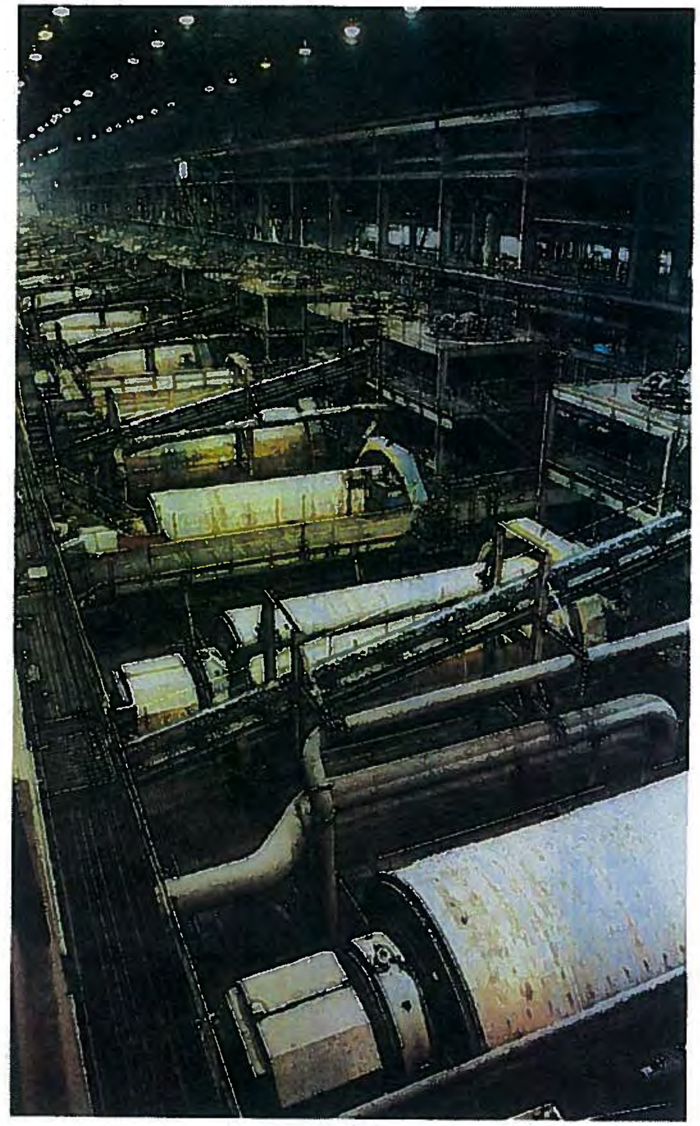

CONCENTRATING & PELLETIZING FLOWSHEET
HEMATITE
MAGNETITE
HEMATITE & MAGNETITE
FLUXSTONE
CRUSHER
ORE BARN
PRIMARY MILL
INTERMEDIATE CRUSHING
PEBBLE MILL
CYCLONE
THICKENER
COBBERS
MAGNETIC FINISHER
FLOTATION
CONCENTRATE THICKENERS
CONCENTRATE SLURRY TANK
FILTERS
DRYER
BALLING DRUM
KILN
PELLET STOCK PILE
PELLET LOAD OUT BIN
COOLER
TRAVELING GRATES
FLUX CIRCUIT
FLUX PILE
BALL MILL
CYCLONE
THICKENER
FLUX SLURRY TANK

Grinding

Liberating the iron mineral requires that the crude ore be ground to the extremely fine consistency of face powder. This process begins in the same way for both magnetite and hematite as crude ore and water are fed into large primary autogenous mills (above). The term autogenous means that grinding media like the steel balls and rods used in some mills are not required. Instead, the tumbling action of the ore in the rotating mills is sufficient to reduce it to a consistency of beach sand. Tilden has twelve primary mills that are 27 feet in diameter and 14-1/2 feet long.

Further grinding occurs in pebble mills (right) which also operate on the autogenous principle. In this case, pebbles about 2 inches in size, which are screened from the primary mill, are used as grinding media. The Tilden concentrator has twenty-four 15-1/2 foot diameter pebble mills. Twelve are 30 feet long and the remainder are 32 feet long.

An intermediate crushing circuit is part of the primary grinding operation. The "critical size" material generated by the primary mills can be crushed and returned to the mills, increasing grinding efficiency and mill feed rates.

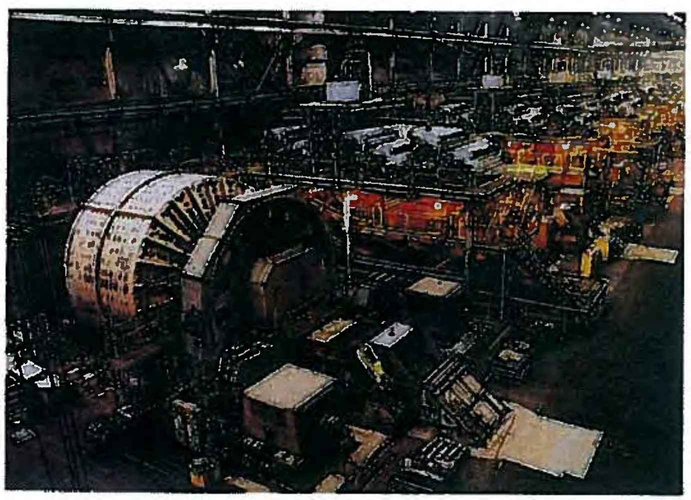


Concentrating Magnetite

Turning low-grade crude ore into high-grade concentrate requires a means of separating the iron particles from the waste rock. In the magnetite operation, magnetic separators known as cobbers and finishers help perform that function.

The mixture of finely ground crude ore and water enters the separator tanks where stainless steel drums with powerful internal magnet systems attract and recover the magnetic iron particles, while the non-magnetic silica is washed away as waste, known as tailings.

Tilden has 54 cobbers in the primary grinding circuit (below and upper right) and 60 finishers (below right). Magnetite processing also utilizes deslime thickeners for hydraulic concentration prior to magnetic finishing and flotation of silica as the final grade control concentrating step.

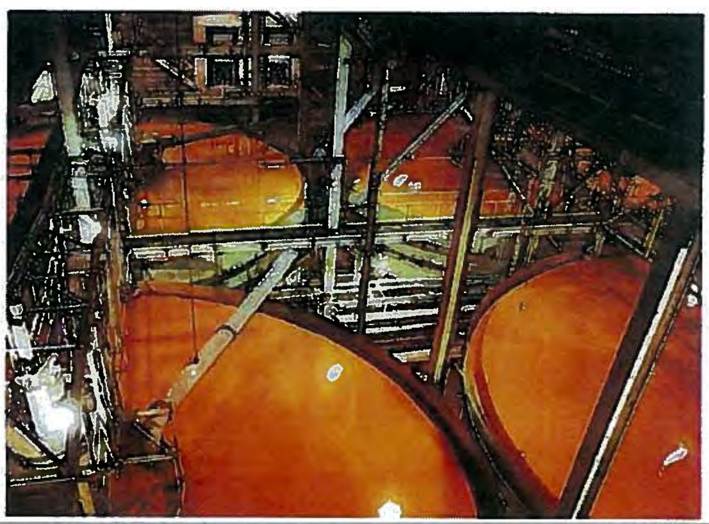


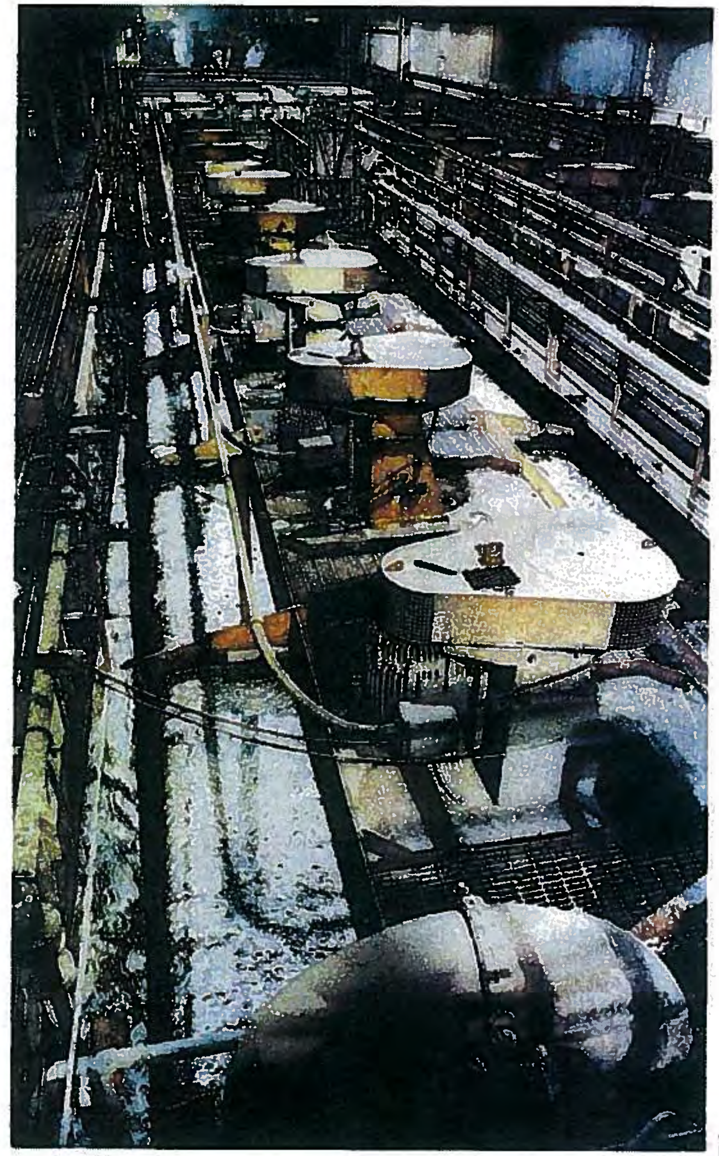
Concentrating Hematite

When processing hematite, Tilden must use a flotation system specially developed for the mine's fine-grained ore, rather than magnetic separation.

The finely ground mineral particles are conditioned by adding caustic soda and a dispersant in the grinding process. Then a cooked corn starch is introduced to selectively flocculate or gather together the very fine iron particles. The separation occurs in twenty-four 55-foot diameter tanks known as deslime thickeners (below) where the flocculated iron particles settle and are recovered in the underflow while the fine silica tailings are carried away in the overflow.

The material is then fed to the flotation circuit consisting of three-hundred 500 cubic foot flotation cells (right) arranged in twelve lines. Here, further separation occurs as silica is removed in the froth overflow through a process known as amine flotation, producing a high-grade iron ore concentrate.





Processing General

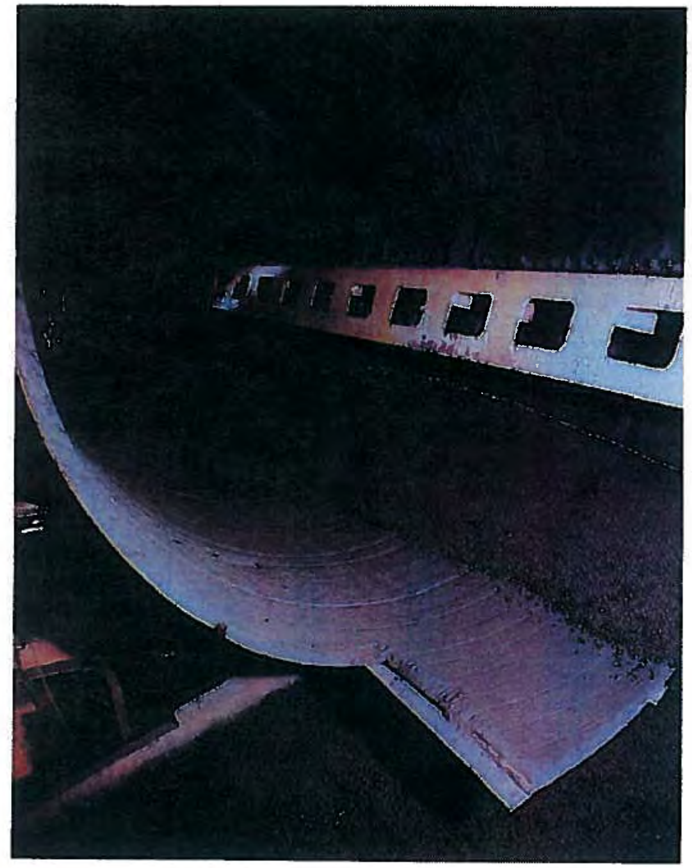
After the mineral has been concentrated using the magnetic or flotation process, dewatering begins as the material is thickened in large settling tanks.

From the thickener, the mixture of high-grade iron ore and water is pumped into concentrate slurry storage tanks.

To produce fluxed pellets, a mixture of limestone and dolomite is also ground to a very fine size and added to the concentrate slurry tank at the desired rate. If it is not added to the pellets, the limestone and dolomite must be added at the blast furnace. The specific mix and amount of flux material in the pellets can be tailored to the customer's specification.

Filtering is the final step in the concentrator. Large vacuum disc filters (below) dewater the concentrate in preparation for pelletizing. The same filters are used for both types of concentrate, however, steam is used when hematite is filtered because it is more difficult to dewater.

To achieve the desired final moisture level for pelletizing, a portion of the product is processed in a rotary dryer and then conveyed to the pellet plant.



Pelletizing

Iron ore concentrate filter cake provides the ingredients for the mine's final product, but it must be put in a form which is suitable for shipping and for handling in the blast furnace.

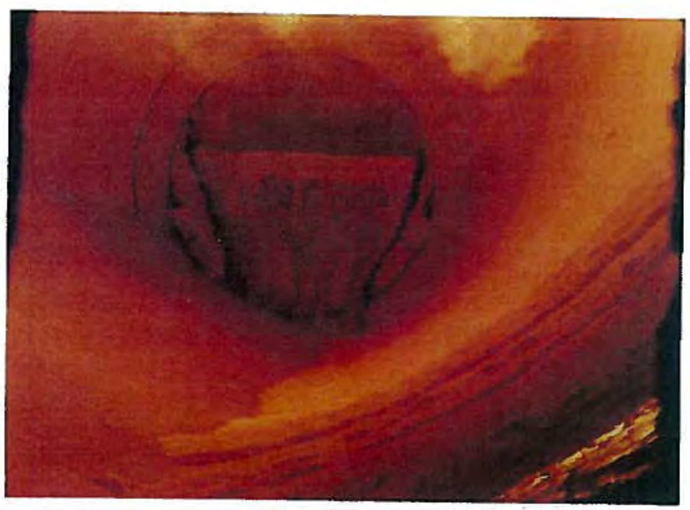
The powdery iron ore concentrate is mixed with a small amount of bentonite clay binder and then rolled into marble-sized pellets in balling drums (above). Tilden has 14 balling drums which are 12 feet in diameter and 33 feet long.

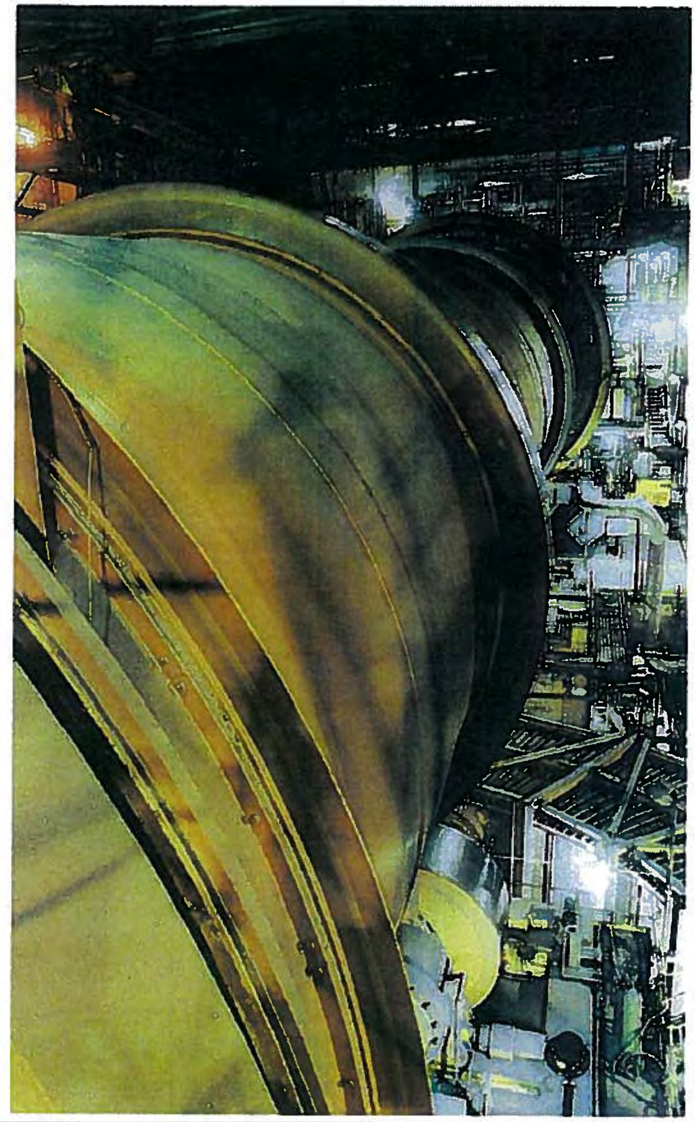
Pelletizing

Leaving the balling drums, the pellets are the proper size and shape, but they are too soft for handling. The unfired pellets, or "green balls," are conveyed to the travelling grate furnace where the temperature is gradually increased to dry and pre-heat them. The pellets then enter the huge rotary kilns (interior – below / exterior – right) where they are hardened by firing at temperatures above 2200 degrees Fahrenheit.

The two kilns at Tilden are 25 feet in diameter and 160 feet long. They can burn natural gas and coal as fuel. Because of the large amount of fuel required to maintain this process, special heat recuperation or recycling systems have been designed to achieve energy conservation.

The pellets leaving the kiln enter an annular cooler where they are cooled to a temperature suitable for conveying. There are two grate-kiln cooler systems, each capable of 13,000 to 18,000 tons per day of pellet production, depending on the grade of pellets being produced.



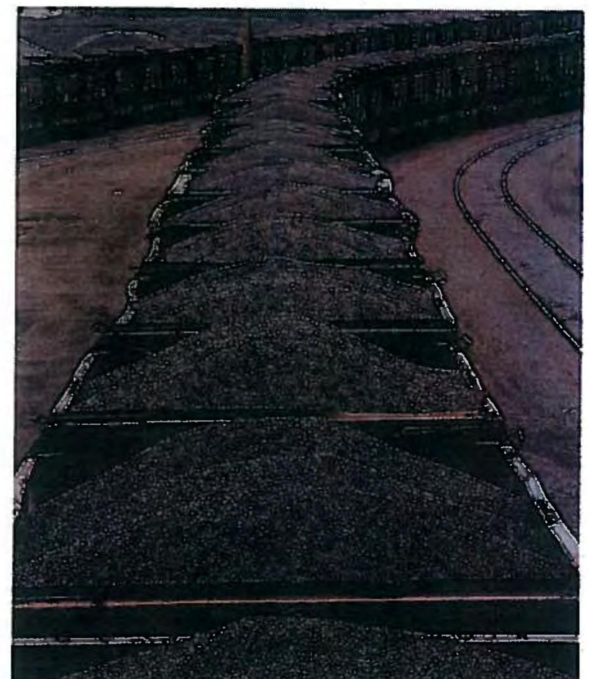


Control Room

In the control room at Tilden, experienced personnel use the latest technology and computerized systems to monitor and control every aspect of the concentrating and pelletizing process. These systems ensure that quality and production are optimized and the final product meets all customer requirements.

Shipping

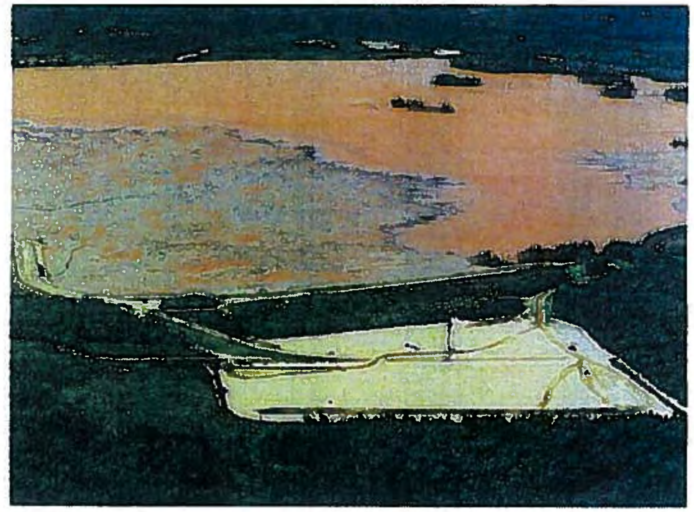
The pellets are conveyed from the plant to the stockpile or the load-out bin. The stockpile has a capacity of 3,000,000 tons of pellets, while the load-out bin can fill up to 450 railroad cars per day. Pellets travel by rail to ports in Marquette and Escanaba where they are shipped by Great Lakes ore carriers to steel mills in the United States and Canada. Unit trains are used for some Tilden customer requirements.



Environment

The Tilden Mine was designed to include modern pollution control processes and equipment. Water receives careful attention at both ends of the processing operation.

To meet the need for a dependable source of water, the Greenwood Reservoir (below) was constructed on the middle branch of the Escanaba River. This man-made lake includes 1,400 acres, 26 miles of shoreline and 13 major islands. In addition to providing water for the mine, the Reservoir is open to the public for a variety of recreational activities.



Nearly all of the water used in the plant is re-circulated through the use of large tailing thickeners and a re-use water pond system. Fresh water use is approximately 5 percent of total process water requirements.

The water used for processing the iron-bearing material through the concentrating process also carries the silica, or tailings, to a large impoundment known as a tailings basin. At the Gribben Basin (above), which serves the Tilden Mine, the water is decanted and clarified so it can be returned to the watershed meeting all government clean water standards.

Air quality is also important, and Tilden uses modern electrostatic precipitators to remove particulate matter from its pelletizing waste gas streams entering the environment.

Continual contact is maintained with regulatory agencies, and a technology improvement effort ensures that Tilden minimizes the impact of its activities on air, water and land.

Attachment 6-B

Rock Stockpile Reclamation

Alan Koski, CCMO Mine Engineering

Cleveland-Cliffs
MICHIGAN OPERATIONS

Cleveland-Cliffs
MICHIGAN OPERATIONS

CCMO RECLAMATION VISION

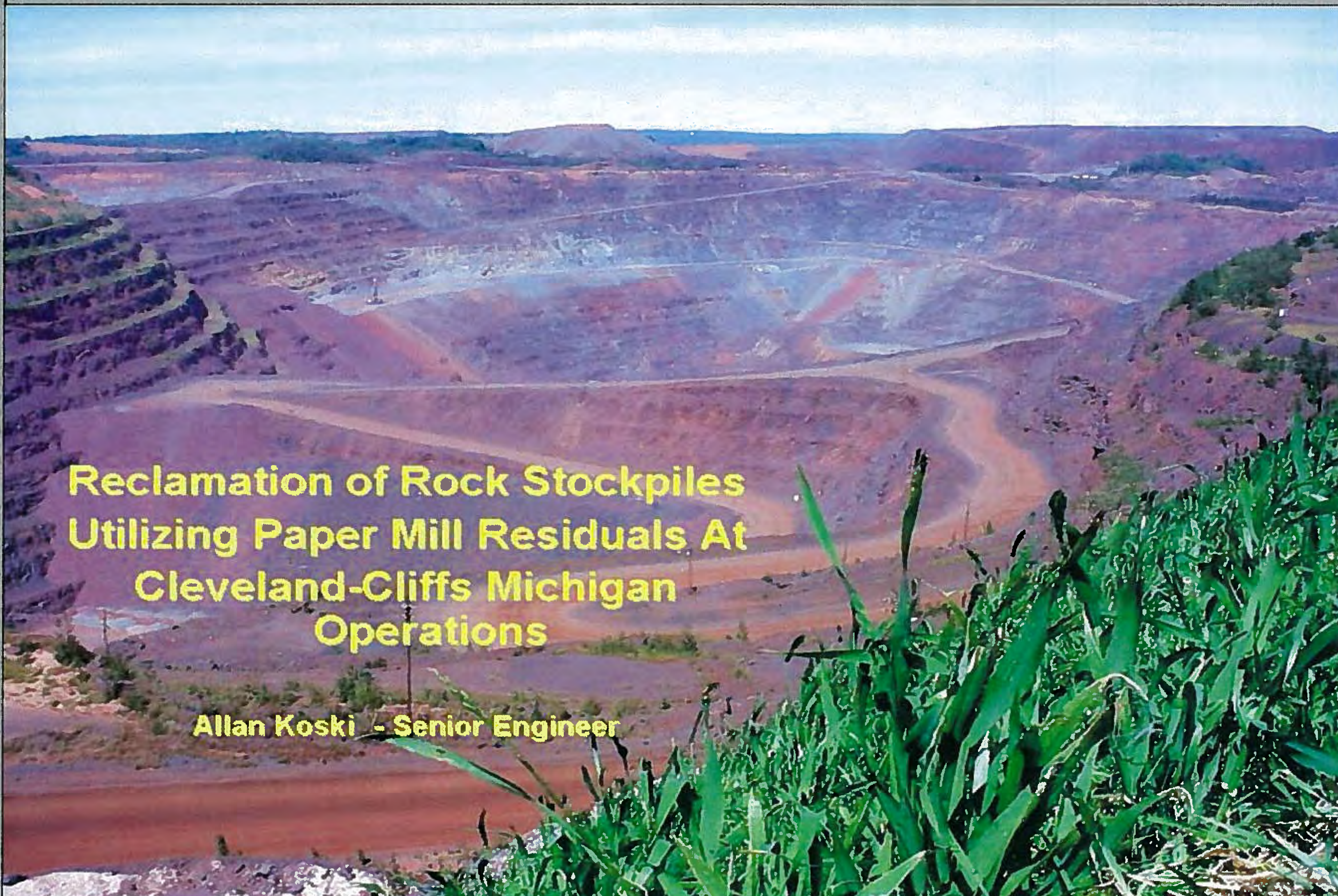
CCMO is committed to Leadership in the Mining Industry, including Excellence in Reclamation:

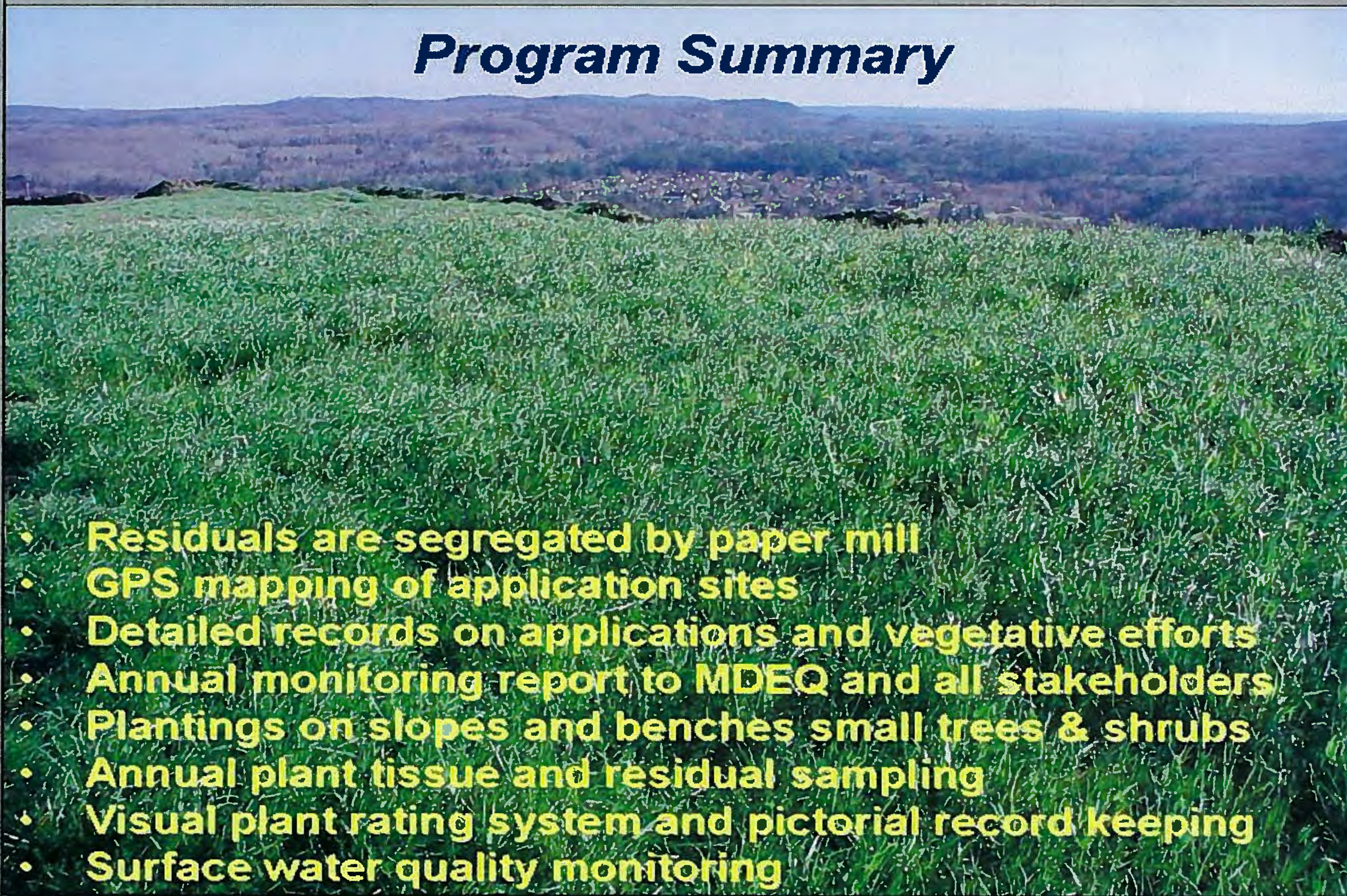
- By managing and developing reclamation activities that protects local economies, CCMO's economic future, and preserving and protecting natural resources and ecosystems.

- By a commitment to open communications with members of the communities in which we operate.

- By making efforts to be aware of, and to comply with all environmental regulations.

- By implementing innovative, sound reclamation practices with cost-effective and measurable results.


Reclamation of Rock Stockpiles
Utilizing Paper Mill Residuals At
Cleveland-Cliffs Michigan
Operations
Allan Koski - Senior Engineer


Program Summary
• Residuals are segregated by paper mill
• GPS mapping of application sites
• Detailed records on applications and vegetative efforts
• Annual monitoring report to MDEQ and all stakeholders
• Plantings on slopes and benches small trees & shrubs
• Annual plant tissue and residual sampling
• Visual plant rating system and pictorial record keeping
• Surface water quality monitoring


Before
After

Attachment 6-D

Tailings Basin

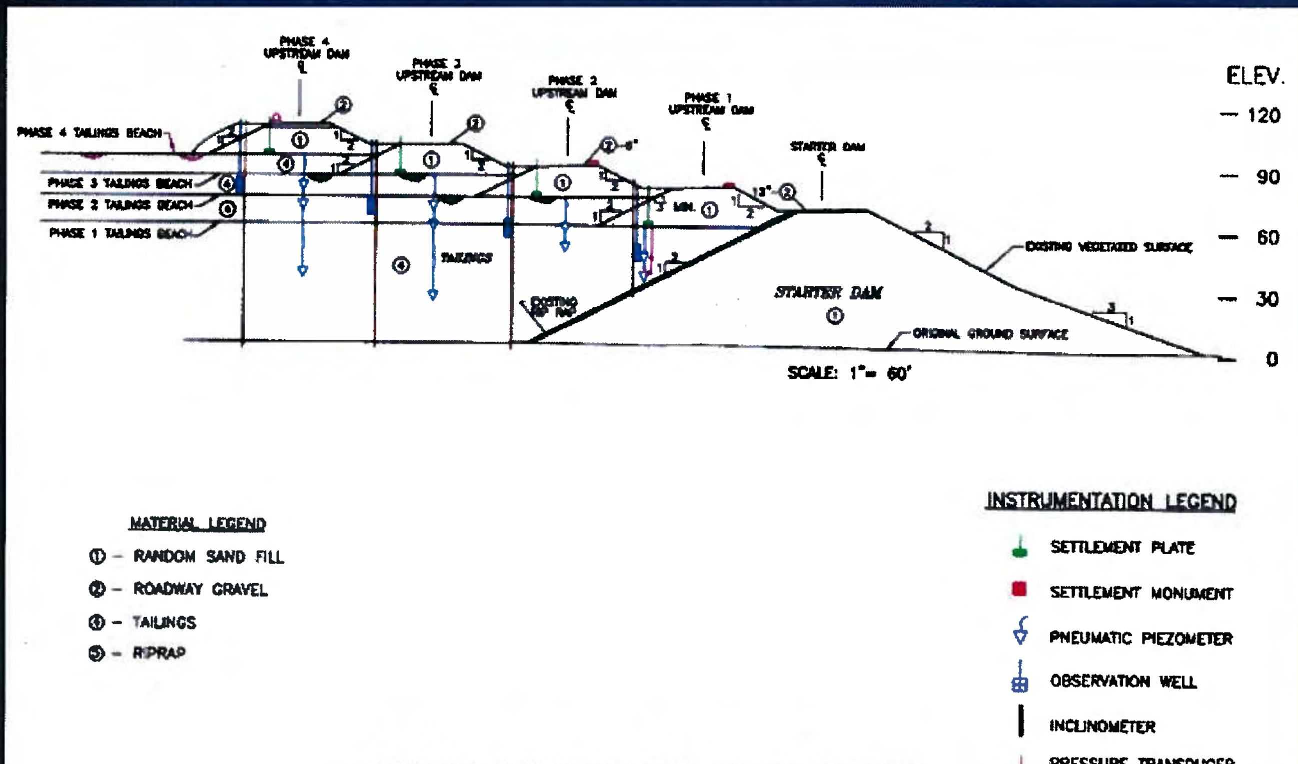
Construction and Maintenance

Karla Brudi, CTG Engineering

Cleveland-Cliffs
MICHIGAN OPERATIONS


Empire Mine
Tilden Mine
Empire Basin
Cleveland-Cliffs
MICHIGAN OPERATIONS

Upstream Construction Example



TYPICAL UPSTREAM DAM CROSS-SECTION

FIGURE: 6–2

Attachment 6-E

Republic Mine

Mine Reclamation
Tailings Basin Reclamation
Wetlands Preserve

John Meier

Cleveland-Cliffs
MICHIGAN OPERATIONS


Republic Mine

Republic Wetlands Preserve

Creating a wetlands preserve such as this one involves careful planning and engineering before construction begins. The plans and procedures to create the wetlands must meet with the approval of regulatory agencies, in this case the Michigan Department of Environmental Quality, the Michigan Department of Natural Resources, and the U.S. Environmental Protection Agency, before the work can take place.

Building the new wetlands involves the use of heavy equipment to divert existing water. Berms are constructed creating channels to retain water and shallow open water pools are filled. All of this helps new plant life grow on previously infertile soil and fosters an environment that allows birds, reptiles and mammals to flourish.

The Republic Wetlands Preserve is a work in progress. It's home to the animals seen here and to a large number of other species.

The preserve will allow the banked wetlands to provide mitigation for the operating mines in Michigan managed by The Cleveland-Cliffs Iron Company, as they unavoidably impact existing wetlands. This will allow the mines to continue to provide a vital raw material--iron ore--to the North American economy, while providing a livelihood for more than 1,900 residents and an economic impact to the region of more than $370 million each year.

That's a win-win situation for the communities, both nature's and man's.

Republic Wetlands Preserve

- 2,300 Acres of total preserve area
- 615 Acres of new wetlands created
- 300 Acres of wetlands seeded
- 60,000 Wetland plants planted
- 225,000 Wetland trees planted

The wetlands environment is enhanced by seeding, mulching and fertilizing large open spaces. This creates fields and meadows where small animals and reptiles can find food and shelter.

Tree planting also takes place with species suitable for this environment. In this case, cedar and tamarack trees were planted, which will eventually provide excellent thermal cover and browsing opportunities for whitetail deer.

Despite the challenges the inert tailings present for growing vegetation, the tailings are somewhat efficient for creating wetlands. They hold water well, even in drought conditions and that's important in the creation of the different types of wetlands at Republic. Submergent, emergent and forested wetlands are being created. These will support grasses, shrubs and even trees as habitat for wildlife.

In addition, small ponds and marshy areas will support aquatic plants, fish, reptiles and waterfowl.

It's this diversity that makes wetlands such an important wildlife habitat.

Creating a diverse wetlands provides an important area for breeding for both fish and wildlife. In addition, feeding areas are created with the wetlands providing a secure home for the assorted species of reptiles and animals.

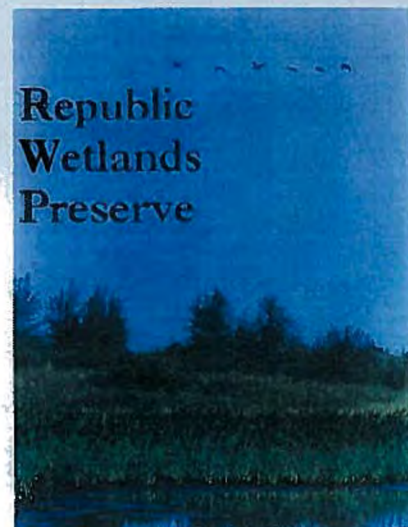
The future is bright for the Republic Wetlands Preserve. While work continues, it is our intention to eventually place all 2,300 acres in a Conservation Easement for the benefit of the State of Michigan. This easement will protect the preserve from future development.

In the meantime, Cliffs' personnel, using the latest technology including Global Positioning Satellite systems, will assist environmental consultants and the regulatory agencies to monitor growth and activity at the site.

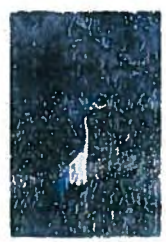
Eventually, the site will become a vast forested wetlands, with clear pools, lively marshes and lush, green meadows. A former tailings basin area returned to a natural state, with little to remind anyone that it had once been used in mining and processing iron ore.

This part of nature, borrowed for a few decades by man for his use, will again become a vital part of Michigan's Upper Peninsula. More than 2,000 acres teeming with life and taking its place in the natural environment.

The Cleveland-Cliffs Iron Company is a subsidiary of:
Cleveland-Cliffs Inc.
1100 Superior Avenue
Cleveland, OH 44114-2589
www.cleveland-cliffs.com



Wetlands creation for generations to come...



The Republic Mine during its operating days

For decades the Republic Mine in Michigan's Upper Peninsula mined a rich deposit of iron ore and processed i into pellets. These iron ore pellets helped forge the steel used to make automobiles, bridges, buildings and more.

Like all mines, however, Republic's useful life ended and it closed in 1996. Now, through a pioneering program the area surrounding the mine is coming back to life with t sounds of birds and animals as more than 600 acres of wetland habitat are being created where none existed befo

The manager of the Republic Mine, The Cleveland-Cliffs Iron Company, also manages two other mine partner-ships nearby. These open pit mines require large operatin areas and, as they expand, they unavoidably impact wetlan and must mitigate this impact by creating new wetlands.

Through a unique arrangement, a wetlands mitigati bank is being built by revegetating and creating wetlands at the Republic Mine's tailings basins, to be used as replacem wetlands for areas impacted by current mining operations.

New wetlands are being created on several tailings basins. The tailings, deposited in these basins during the li the mine, are the waste product from the concentrating process. They are extremely fine, sandy particles. Simply put, an inert soil that is challenging to revegetate.

54th Annual Institute on Lake Superior Geology

Field Trip 7

GEOLOGY OF THE KEWEENAWAN BIC INTRUSION

Dean Rossell

Kennecott Minerals Company

The Geology and Geologic Setting of the BIC Cu-Ni-PGE Prospect, Baraga County, Michigan U.S.A.

Introduction

The BIC mafic/ultramafic intrusion is located in Baraga County, Michigan, approximately 8 km southeast of the town of L'anse, Michigan. The roughly 1.1 km by 0.4 km, oval shaped intrusion forms a prominent hill with good exposures of the principle units that comprise the intrusion. The BIC intrusion has not been dated yet. However, based primarily on compositional similarities, Kennecott geologists believe it is similar in age to the mafic/ultramafic intrusion that hosts the Eagle Cu-Ni-PGE deposit, located ~35km to the east (fig 1), which has been recently dated at 1107.2+/- 5.7ma (Ding, 2007)

The BIC intrusion has been the target of periodic exploration by Kennecott Exploration Company since the first discovery of Cu-Ni-PGE mineralized boulders near the intrusion in the mid-1990's. The first drill hole into the intrusion, in 1995, was positioned at the south edge of the intrusion. The hole (BIC95-1, fig. 3) intersected ~3 m of disseminated sulfide mineralization in olivine melagabbro at the base of the intrusion, averaging 0.43%Cu, 0.32%Ni, 0.325ppm Pt and 0.345ppm Pd.

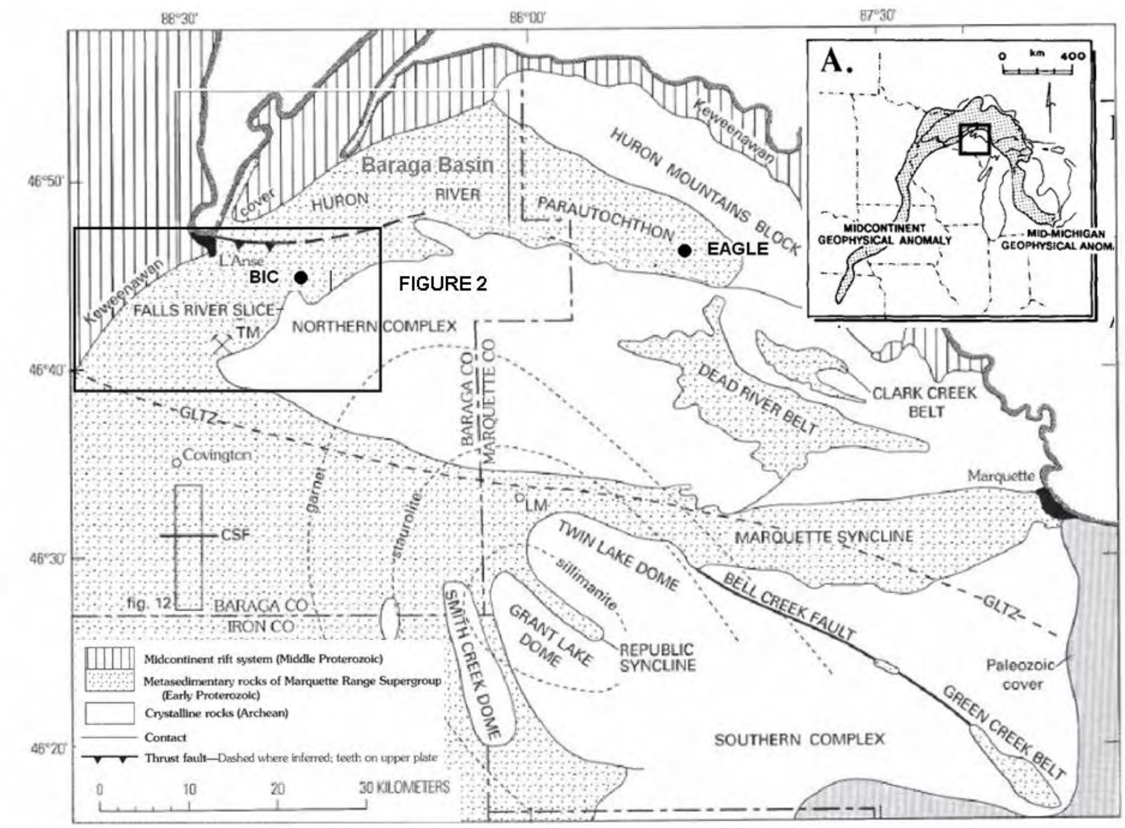


Figure 1) Geology map of the northern portion of the Upper Peninsula of Michigan showing the location of the Baraga Basin and the BIC intrusion. Modified from Gregg (1993)

No significant Cu-Ni-PGE resource has been identified at the BIC prospect yet. However, a drill hole completed by Kennecott Minerals Company in 2006 (07BIC-007), intersected 16.47m averaging 0.88%Cu, 1.00%Ni, 0.679ppm Pt, 0.991ppm Pd and 0.104ppm Au . This interval included a 2.8m interval with bands of massive sulfide, located in the meta-sediments immediately below the base of the intrusion, which averaged 1.66%Cu, 4.23%Ni, 1.383ppm Pt and 2.521ppm Pd. The metal tenor of the massive sulfide bands is comparable to some of the massive sulfides in the Eagle deposit. This could suggest that there is still some potential for a high grade massive sulfide body in the less explored portions of the BIC intrusion.

Previous Geologic Studies

No detailed geology map covers the area immediately around the BIC intrusion. The geology shown in Figure 2 is, in part, modified from data included in the USGS 1:62,500 scale open file geology map of the Precambrian geology of the Dead River, Clark Creek and Baraga Basins (Cannon, 1977). The area in figure 2 is also covered by the Iron River 1º x 2º quadrangle (Cannon, 1986). Geology in the Taylor Mine area (fig. 2) is compiled and modified from detailed mapping by Klasner (1972) and Klasner and others (1991).

Ojakangas (1991) discussed stratigraphic correlations of Paleoproterozoic rocks in the area shown in figure 2. Gregg (1991) and Klasner and others (1991) described Penokean age deformation in the same area. The Archean geology to the southeast of the BIC intrusion is described in an unpublished master's thesis by Turner (1979). A review of the Paleoproterozoic stratigraphy in the Baraga Basin, including the Taylor mine area, was recently undertaken by Gabe Nelson as part of a Masters thesis at Acadia University under Pier Pufal.

The above data sources were supplemented by periodic reconnaissance mapping by me during the period 1999-1996. This work was augmented by regional geophysical studies and drilling programs carried out by personnel of Kennecott Exploration Company, Kennecott Minerals Company and various contractors. The more detailed geologic data from the BIC area is compiled from work by me, other Kennecott Exploration and Kennecott Minerals geologists, contract geologists and reports on petrography completed for Kennecott by Barnett (1995), Hauck (2001) and Johnson (2007).

Regional Setting

The BIC intrusion cuts Paleoproterozoic sediments in the southwestern portion of the Baraga Paleoproterozoic sedimentary basin (fig 1). The Baraga basin is bounded to the north and south, and underlain by Archean crystalline rocks. The Baraga basin merges with the Paleoproterozoic sediments of the Marquette Syncline southwest of the BIC intrusion (fig 1). The Archean, Paleoproterozoic and Mesoproterozoic geology is briefly summarized below.

<u>Archean</u>

The Archean terrane to the immediate south of the BIC intrusion (fig.2) is comprised largely of coarse grained, felsic gneiss and lesser amphibolite intruded by a variety of small mafic to ultramafic intrusions. Although there has been little mapping to confirm it, the gneissic rocks are most likely a continuation of the gneiss, intrusions and lower metamorphic grade supracrustal rocks (Marquette Greenstone Belt) that collectively comprise the Northern Complex (fig 1) to the east. A tonalitic intrusion dated at 2703 Ma and a rhyolite dated at 2780 Ma (Sims, 1993), are the only available age dates from the Northern Complex.

Paleoproterozoic

The recent discovery of the Sudbury ejecta horizon in the Baraga Basin (see below) constrains the bulk of Paleoproterozoic sedimentation to post 1850ma. Gregg (1993) divided the Baraga basin into two principle structural domains; the northern Huron River parautochthon and the southern allochthonous Falls River slice. Gregg proposed the boundary between the terrranes, which is marked by an abrupt change in structural style, is a south dipping thrust fault that he named the Falls River Thrust (fig. 2).

Paleoproterozoic sediments to the north of the Falls River Thrust are characterized by weakly asymmetrical, relatively open folds with shallow axial plunges to the northwest or southeast. A single, southwest dipping, axial planar foliation is evident in most pelitic and siltstone horizons. Immediately south of the Falls River Thrust, folds are tight to isoclinal, generally overturned and often recumbent. In the Falls River slice, larger scale folds are overprinted by a second generation of folds with an associated crenulating foliation that is particularly evident in pelitic sediments. Boudinaged and folded quartz veins and lenses are prevalent in coarser-grained meta-greywacke beds in the Falls River slice.

Klasner and others (1991) mapped a thrust fault in the Komtie Lake area, south of the BIC intusion (fig. 2). They reported that a vertical exploration drill hole, located on the south side of Komtie Lake, penetrated 30 m of Archean gneiss followed by 3 m of mylonite before intersecting 45 m of Paleoproterozoic sediments. They proposed an approximately east-west striking and south dipping thrust fault that brought Archean gneiss over a thin veneer of the basal Paleoproterozoic sediments. They extended the fault westward to include strongly foliated rocks exposed along Plumbago Creek (fig 2). I extended the Komtie Lake thrust fault further to the northeast in figure 2, to an area where magnetic anomalies originating in the Paleoproterozoic sediments appear to continue under exposures of Archean gneiss. This extension has not been confirmed by mapping.

Exposures of pelitic rocks in the immediate area of the Taylor mine (stop 3, fig. 2) generally lack the prominent crenulating cleavage seen in pelitic rocks exposed all along Taylor Creek further to the north (stop 4, fig. 2). Drill hole T-5, a 68.5 m deep vertical exploration hole collared northeast of the Taylor mine pit (fig. 2), bottomed in mylonitic rock. I propose that there is another generally east-west striking thrust fault north of drill hole T-5, separating the overriding Taylor Mine slice from the more deformed rocks of the Falls River Slice. Alternatively, the fault could be the westward continuation of the Komtie Lake thrust fault.

Historically, deformation of the Paleoproterozoic sediments in the western portion of the Upper Peninsula has been attributed to a series of collisional events between 1888 Ma and 1830 Ma that collectively make up the Penokean orogeny (Schultz and Cannon, 2007). However, Schultz and Cannon (2007) point out that there is evidence of vertical faulting and uplift that significantly post date1830 Ma. They concluded that this younger deformation cannot be attributed to the Penokean orogeny and that it is more likely of Yavapai age.

Mesoproterozoic

Mesoproterozoic flood basalts associated with the Keweenaw Flood basalt Province are exposed along the length of the Keweenaw Peninsula and 30km southwest of the BIC intrusion at Silver Mountain, Michigan. The Keweenaw Flood Basalt province represents the exposed portion of the Midcontinent Rift system in the Lake Superior region. The Midcontinent Rift forms a prominent gravity anomaly that can be traced from the Lake Superior region southwest into central Kansas, and southeastward into southern Michigan. The total length of the geophysical feature is in excess of 2000 km (Hinze and others, 1997). Seismic data indicates the rift below Lake Superior is filled with more than 25km of volcanics buried beneath a total thickness of up to 8km of rift filling sediments (Bornhorst and others, 1994). The estimated volume of magmatic rocks associated with the rift is greater than 2 million cubic kilometers (Cannon, 1992).

The Keweenaw Flood Basalt province was formed over an approximately 23 million year period, from ~1111 Ma. to ~1089 Ma. Volcanism was bimodal, but with preserved basaltic rocks much more abundant than rhyolitic rocks. Volcanism occurred in two distinct phases, with an approximately 5 million-year hiatus between phases (Miller, 1996). In Michigan and Wisconsin, the early phase volcanics are comprised of the Sieman's Creek formation and volcanics of the Powdermill group (Wiband and Wasuwanich, 1980). The Portage Lake volcanics comprise the younger phase. The early phase volcanics are primarily reversely polarized. The Portage Lake volcanics are normally polarized. A mantle plume model has been widely evoked to explain the staged evolution and large volume of magmatic products associated with the Midcontinent Rift (Nicholson, 1997).

Red bed sandstones (Jacobsville Sandstone) shed off the horst block formed during inversion of the Midcontinent Rift, cover Paleoproterozoic sediments west of BIC (fig. 2). Rift inversion may have begun as early as 1080 Ma and was completed by about 1040 Ma (Cannon, 1994). The probable cause of compression was continental collision in the Grenville province (Cannon, 1994).

Paleoproterozoic Stratigraphy

Archean rocks are either unconformably overlain by, or in fault contact with, Paleoproterozoic meta-sediments along the southern margin of the Baraga Basin. Ojakangas (1994) has correlated sediments in the Baraga Basin and western Marquette trough with the Baraga Group, the youngest of the three dominantly clastic sedimentary groups that comprise the Marquette Range Supergroup. He concluded, on the basis of paleocurrents, paleogeographic setting and isotopic data that the best tectonic model for Baraga Group sedimentation is a northward migrating foreland basin.

Quartzites at the base of the Paleoproterozoic sedimentary sequence in the Baraga basin north of the Falls River thrust and in the Canyon Falls area (stop 1-fig. 2) are correlated with the Goodrich formation by Ojakangas (1994). The basal quartzites at both these localities appear to rest unconformably on Archean basement. The quartzites range from thickly to thinly bedded, with locally well developed planar and trough cross bedding. Quartzites in the Baraga basin are typically arkosic with conglomerate lenses. Ojakangas (1994) proposed that the Goodrich quartzites were deposited in a tidal environment. In the Baraga Basin, the Goodrich formation ranges in thickness from less than a meter in the eastern portion of the basin, to approximately 40 m in the western portion of the basin (Nelson, 2006).

I interpret widely scattered outcrops of similar appearing quartzite exposed along the margins of the Archean to the south and east of the BIC intrusion as equivalents of the Goodrich quartzite described above. However, in most places they appear to be in fault contact with the Archean. Klasner and others (1991) interpreted strongly foliated, quartz rich schists along the north side of Plumbago Creek in the Taylor mine area (fig. 2) as mylonitic textured Archean gneiss. I have examined some of these outcrops and feel they could, in part, be strongly foliated arkosic Goodrich quartzite. The proximity of the sheared "quartzite" with iron formation exposed along the banks of Plumbago Creek has potential stratigraphic implications in the Taylor mine area.

The Goodrich formation is overlain by the Michigamme formation, the uppermost formally recognized formation in the Baraga Group. Leith, et al (1935) divided the Michigamme formation into three principle members which, in ascending order are: the Lower Slate member, the Bijiki iron formation, and the Upper Slate member. Kennecott geologists have generally used this nomenclature for describing stratigraphic relationships in the Baraga Basin. However, in the western portion of the Baraga Basin, the Goodrich formation quartzites are immediately overlain by a thin interval (typically less than 20m thick) of inter-bedded chert and iron rich carbonate. Ojakangas (1994) suggested that this cherty horizon may be the equivalent of the Bijiki iron formation and that the Lower Slate member is missing in parts of the Baraga basin. However, Kennecott geologists believe this is a separate unit below the Lower Slate member and informally refer to it as the Chert Carbonate member. That informal designation is used in the rest of this field guide and in figure 2.

William Cannon (personal communication) has identified layers with accretionary lapilli, pumice grains and, at one location, quartz grains, with shock lamellae from bedrock exposures and core samples of the Chert Carbonate member in the Baraga Basin. Cannon has proposed that these are ejecta from the 1850 Ma Sudbury impact event and correlated them with other ejecta horizons previously identified in Ontario and Minnesota (Addison et al, 2005). Kennecott drill hole 07BIC-033, the deepest hole completed at the BIC prospect, intersected intervals with probable accretionary lapilli and pumice fragments (Cannon, personal communication) in cherty rocks starting at a depth of 586 m. The likely presence of the Sudbury ejecta layer in the BIC drill hole provides confidence that the more deformed rocks in the southwestern portion of the Baraga basin (south of the L'anse thrust fault in figure 2) are stratigraphically correlative with the rocks in the northern portions of the Baraga Basin.

The Chert Carbonate member and Sudbury ejecta layer is overlain by dominantly black to dark gray, thinly bedded, meta-siltstone and pelite in the Baraga Basin. The pelitic rocks are often graphitic and sulfide rich and contain only minor intervals of fine-grained greywacke. As mentioned above, Kennecott geologists believe this is the Lower Slate member of the Michigamme formation. This siltstone-pelite dominated interval increases from 20-90 m in the northern part of the Baraga Basin to thicknesses I speculate might be greater than 200 m in the vicinity of the BIC intrusion. However, structural complexities and insufficient drilling make accurate determinations of the thickness of this sequence currently impossible in much of the southern portion of the Baraga Basin.

In the Taylor mine area (stop 3-fig.2) the Lower Slate member is overlain by the Bijiki iron formation. The Bijiki iron formation is primarily comprised of thinly bedded, black and white chert with lesser siltstone, iron carbonate and iron oxides (Ojakangas, 1994). In the immediate Taylor mine area the Bijiki iron formation ranges from 20-80m in thickness (Ford Motor Company reports).

A Kennecott Exploration drill hole, ALB95-3, located approximately 2.7km west of the Taylor mine (fig. 2), intersected 280 m of banded iron formation, with lesser intervals of graphitic slate, starting at a depth of 110 m and continuing to the bottom of the hole. Bedding angles to core, along with the lack of any compelling evidence of fold or fault repetition, suggest that this is likely to be close to a true thickness. A second hole, ALB95-2, collared 1.1 km further to the west, intersected 194 m of iron formation. Both holes were terminated while still in iron formation so the total thickness of iron formation at this location is unknown. Kennecott geologists believe the iron formation in both holes is the Bijiki indicating a rapid westward thickening of the unit. This thicker part of the Bijiki is within a rhomb shaped magnetic and gravity high. The rapid westward thickening of the iron formation, and shape of the coincident geophysical anomalies, might be evidence of a fault bounded, second order basin that formed during deposition of the Lower Slate and Bijiki iron formation.

The BIC intrusion cross cuts an approximately 15km long linear magnetic anomaly. Drilling and mapping by Kennecott geologists has confirmed that the linear magnetic anomaly is caused by abundant pyrrhotite in graphitic sediments. The sediments contain numerous thin bands of contorted quartz and 0.5-1cm thick bands and lenses of semi-massive pyrrhotite and pyrite with minor sphalerite and chalcopyrite. The ratio of pyrrhotite and pyrite varies considerably along strike, and within a drill intersection, significantly affecting its magnetic susceptibility. Similar sulfide rich sediments are seen immediately below the Bijiki iron formation at the Taylor mine and in a 25-35m interval immediately above the Bijiki iron formation in drill holes ALB95-2 and ALB95-3 (pyrite rich in hole ALB95-3 and pyrrhotite rich in hole ALB95-2). The author proposes that these sulfide rich, variably magnetic sediments are the continuation of the Bijiki iron formation member northward into the BIC area. However, this important marker horizon has not been identified anywhere else in the northern part of the Baraga basin.

The Bijiki member is overlain by the Upper Slate member in the Taylor mine and BIC prospect areas. The Upper Slate member contains a significant percentage of greywacke inter-bedded with siltstone and pelite distinguishing it from the Lower Slate member. Ojakangas (1994) reported that greywacke beds made up 18% of a measured section in the Silver River north of the BIC intrusion. The greywacke beds are commonly graded and contain rip ups and other features indicative of deposition by turbidity currents.

<u>Baraga-Marquette Dyke Swarm</u>

The Baraga-Marquette dyke swarm is comprised of more than 150 diabase dykes (Green and others, 1987). The primarily east-west trending dikes form a belt that extends from the northern edge of the Baraga basin at least 75 km southward into southern Marquette County. Although most dykes in the swarm are less than 30 m thick, individual dykes are up to 185 m thick and can be traced for up to 59 km (Green et al., 1987).

The majority of the known dykes are reversely polarized, forming prominent magnetic linear anomalies on magnetic maps. None of the diabase dykes have been dated. However, the measured diabase dyke paleomagnetic pole position in the Marquette area is virtually identical to that of reversely magnetized intrusions from the Thunder Bay area (Wilband and Wasuwanich, 1980). Sutcliff (1987) reported an age of 1109ma for the reversely polarized Logan sills in the Thunder Bay area.

The dykes typically have subophitic to diabasic textures and contain 50-70% plagioclase, 30-50% clinopyroxene and 1% or less olivine and Fe-Ti oxides. Most dykes are relatively fresh with little sign of alteration (Wilband and Wasuwanich, 1980). Most of the reversely polarized dykes have high TiO_2 (3-5%), P_2O_5 (0.30-0.55%) and <15% Al_2O_3 (Wilband and Wasuwanich, 1980).The dykes also typically have high Cu (300-500ppm) and low Ni (<100ppm) contents (Kennecott data).

Interestingly, no reversely polarized dykes are evident in magnetic data sets north of the Falls River thrust fault (fig. 2). This might suggest that the fault played some role in localizing the reversely polarized dykes of the Baraga-Marquette dyke swarm.

The BIC Intrusion

The BIC intrusion is located about 35km southwest of Eagle and 8km southeast of the town of L'anse, Michigan. The intrusion forms a prominent hill approximately 1100m long by 400m wide. Mapping, geophysics and drilling indicate the intrusion has roughly the same dimensions as the hill at bedrock surface (fig. 3). Although not well constrained along much of the intrusion, based on the drilling completed, the intrusion appears to be generally V shaped in cross section. Drilling and mapping in the eastern portion of the intrusion suggest the southern margin of the intrusion dips moderately to the north (fig. 4). Knowledge of the northern contact is limited, but it appears to be steeply, south dipping.

A much smaller, shallow bowl shaped intrusion, referred to as Little BIC, was located just to the northwest of the BIC intrusion during 2006 drilling (fig. 3). The smaller intrusion is comprised mostly of relatively olivine rich lithologies very similar to those seen along the base of the main BIC intrusion. This smaller intrusion could be a fault offset of the larger BIC intrusion, or possibly a separate intrusion. The best mineralized intersections in drilling completed through 2007 have primarily come from this smaller intrusion.

Unlike the intrusion hosting the Eagle ore body, the BIC intrusion is distinctly layered. Core logging, thin section work and very limited geochemistry show that the BIC intrusion can be subdivided into three principal units; an upper coarse-grained gabbro, a middle unit comprised of fine-grained gabbro and feldspathic clinopyroxenite, and a lower unit of feldspathic wehrlite and olivine melagabbro. All three units thicken toward the center of the intrusion and thin toward the margins.

The following descriptions of the units are summarized from core logs and observations of outcrops and hand samples. Most of the descriptive mineralogy is taken from unpublished petrography reports prepared for Kennecott Exploration and Kennecott Minerals by Rod Johnson (2007) Steve Hauck (2002), and Bob Barnett (1995).

Upper Unit - Gabbro

The upper gabbro is the thinnest unit with no drill intersections exceeding 75 m (no upper contact has been located so this is only a minimum total thickness). It is exposed in a few scattered locations on the top of the hill. The best exposures are along the drill roads on top of the hill in the eastern portion of the Intrusion.

The upper gabbro is an altered, medium to coarse-grained, oxide gabbro with 55% lath like plagioclase and 35% prismatic or granular clinopyroxene. The gabbro contains up to several percent titanomagnetite, minor apatite and trace olivine. The upper gabbro is moderately to strongly magnetic.

Strong alignment of plagioclase laths, which can be up to 2cm in length, and prismatic clinopyroxnene creates a foliation in the gabbro in places. In other places, the crystals radiate, creating a stellate pattern. Small patches of granophyre are present in drill core and outcrop.

The upper gabbro is moderately to intensely altered with plagioclase variably altered to sericite and clinopyroxene altered to amphibole and chlorite. Very fine grained hematite coats some plagioclase giving it a pinkish color and titanomagnetite is altered to martite and maghemite. Pyrite occurs as disseminations and rare veins (Hauck, 2002).

Football size and shape pods of strong light green, epidote rich rock are common in outcrop and drill core of the upper gabbro. The pods, which have sharp contacts, can form up to 5% of some outcrops. The shape, size and distribution of the pods suggests that they might be preferentially altered xenoliths or autoliths.

Middle Unit-Gabbro/Clinopyroxenite

The middle unit is comprised of gabbro and clinopyroxenite which forms 3-10m high cliffs around the perimeter of the hill. The middle unit is by far the best exposed unit at the BIC prospect. Intersections in drill core of the middle unit reach 100m in drill holes in the eastern half of the intrusion but it appears to thin to the west.

The unit is comprised of fine-grained, equigranular gabbro and feldspathic clinopyroxenite. The upper few meters of the unit is a fine-grained, strongly magnetic equigranular, oxide rich, cumulate textured gabbro with 40-50% granular clinopyroxene and 20-50% granular titanomagnetite and minor ilmenite. Plagiclase content varies, but is typically less than 40% in this oxide rich part. Biotite and amphibole are minor components in the upper portion of the unit. This magnetite rich interval is present in most holes and creates a distinctive spike in magnetic susceptibility profiles in most BIC drill holes (a magnetic profile is shown for hole BIC02-02 in figure 4)

Magnetite content decreases rapidly with depth in the middle unit and most of the unit below the first few meters is weakly to non-magnetic. Clinopyroxene content increases downward and in the eastern portion of the intrusion much of the lower part of the middle unit is fine-grained, cumulate textured, feldspathic clinopyroxenite. The presence of cumulate clinopyroxenite is suspected in the western portion of the intrusion but not yet confirmed by thin section work.

Alteration is similar to that seen in the upper gabbro with plagioclase largely altered to sericite, carbonate and actinolite and pyroxene is variably altered to chlorite, carbonate and amphibole.

Fine-grained, disseminated chalcopyrite and trace bornite is found through out the unit, generally in trace amounts, but locally up to 0.5%. Minor pyrite and sphalerite are present in western outcrops of the middle unit, in addition to chalcopyrite.

Lower Unit- Wehrlite/Olivine Melagabbro

Unlike the upper two units, which contain only very rare olivine and orthopyroxene, the lower unit is relatively olivine rich and has up to 5% orthopyroxene in some thin sections. The lower unit is poorly exposed, with just a few outcropings along the south side and none on the north side. The unit is best exposed on the west end of the hill. Drilling indicates it is the thickest of the three units and has a thickness of greater than 200 m in drill hole BIC02-02 (fig 4).

The upper portion of the lower unit is comprised of fine grained, moderately magnetic, feldspathic wehrlite and olivine melagabbro with 35-60% cumulate olivine, 10-20% clinopyroxene, 10-34% plagioclase and minor sulfide. Clinopyroxene is either granular or poikolitic on olivine and plagioclase is poikolitic on both olivine and clinopyroxene. Titanium rich phlogopite and amphibole are also minor (1-2%) primary mineral phases. Chromite occurs as grains within olivine and minor titanomagnetite and ilmenite occur as single or composite grains, often subpoikolitic on clinopyroxene.

Barnett (1995) reported olivine compositions for outcrop samples of the lower unit that ranged from fo76 to 83. These values closely overlap with the range of fo76 to 85 reported for olivine melagabbro at the Eagle deposit (Ding, 2008). In most holes, olivine content decrease with depth in the lower unit, while clinopyroxene, plagioclase and sulfide increase. In the eastern portion of the intrusion, this change in mineralogy is accompanied by an increase in grain size in the lower 50m of the intrusion.

Alteration is moderate to severe in the lower unit with olivine partially to completely altered to either iddingsite or serpentine and fine-grained magnetite. Both plagioclase and clinopyroxene are variably altered to chlorite and carbonate. The alteration tends to turn everything green in the most altered samples, often making visual determination of the primary mineralogy difficult in hand and core samples.

Contact metamorphic Aureole

Meta-sedimentary rocks peripheral to the BIC intrusion show the effects of low pressure contact metamorphism. Johnson (2007) studied thin sections cut from drill core samples of meta-sediments peripheral to the BIC intrusion. He divided metamorphic assemblages in the meta-sediments into a proximal granoblastic hornfels, a more distal porphroblastic spotted hornfels, and a regional green schist assemblage.

Within two to three meters of the contact of the intrusion, primary structures and foliations in the meta-sediments are very poorly preserved. The regional metamorphic assemblage is overprinted by a granoblastic assemblage of cordierite, quartz, biotite, vesuvianite and sphene +/- andalusite, sillimanite, kspar and plagioclase. Scattered small pods and veins of coarser grained k-spar and quartz within the granoblastic hornfels suggest localized partial melting of the meta-sediments in close proximity to the intrusion.

The granoblastic hornfels grades outward into spotted hornfels which in some drill holes can be recognized in the meta-sediments10 to 15m from the contact with the intrusion. The spotted hornfels is characterized by the growth of small (<0.5 mm) porphyroblasts in phyllosilicate rich beds. Johnson (2007) reported cordierite, andalusite and sillimanite as the principal prophyroblasts in the spotted hornfels. Johnson also reported that much of the high temperature metamorphic assemblage has been overprinted by a retrograde assemblage with porphyroblasts replaced by chlorite and white mica and biotite by chlorite.

Mineralization

Three types of sulfide mineralization related to the BIC intrusion have been recognized: disseminated chalcopyrite-pyrite mineralization in the middle unit, copper and PGE rich disseminated sulfide mineralization in the lower unit and thin bands of “Eagle like” massive sulfide in the hornfels beneath the intrusion. However, exploration work completed to date at BIC has not yet identified any significant Cu-Ni-PGE resource.

Fine-grained chalcopyrite with trace pyrite, sphalerite and rare bornite is disseminated throughout the middle unit. Limited sampling of this interval in drill hole BIC01-01 gave Cu values up to 0.16% over 1.5 m. However, Ni values were all below 500ppm and Pt and Pd values were all at, or below, the detection limits (Kennecott Exploration data).

Disseminated sulfides are erratically distributed throughout the lower unit In the BIC intrusion. However, sulfide abundance seldom exceeds 5% in most of the drill tested portions of the intrusion. The greatest abundance of sulfide is typically located within a 3-4m interval 1-2m above the base of the intrusion. In the Little BIC intrusion, the abundance of disseminated sulfides reaches 10% over short intervals. Continuous intervals with >4% disseminated sulfides exceeding 20 m have been intersected in some drill holes at Little BIC.

Sulfides in the lower unit are comprised of irregularly shaped, composite grains of pyrrhotite, chalcopyrite and pentlandite that are subpoikolitic on olivine, clinopyroxene, plagioclase, amphibole, ilmenite and titanomagnetite (Hauck, 2002). Cubanite occurs both as lamellae in chalcopyrite and as irregular grains. Recalculating the metal contents of disseminated sulfides to 100% sulfide, BIC and Little BIC disseminated sulfide metal tenors in the lower unit average 12.77% Cu, 5.88% Ni, 10.5ppm Pt and 12.91ppm Pd (avg. 109 samples with 0.9-10% S). In contrast, disseminated sulfides in the Eagle deposit recalculated to 100% sulfide average 6.24% Cu, 6.39% Ni, 1.5ppm Pt and 0.9ppm Pd (avg. 2350 samples with 0.9-10% S). The significantly higher Cu:Ni ratio and greater PGE content of BIC disseminated sulfides compared to Eagle disseminated sulfides suggest a greater silicate melt to sulfide melt ratio (R factor) at BIC.

Thin (<1m) bands of massive sulfide occur in the hornfels within a few meters of the base of the Little BIC intrusion, and in a few holes in the western portion of the BIC intrusion. Two samples of massive sulfide from hole 06BIC-007 (Little BIC intrusion- fig.3), selected to maximize sulfide content, averaged 2.72% Cu, 6.02% Ni, 1.8ppm Pt and 3.1ppm Pd (avg. 35.8% S). The significantly lower Cu and PGE tenors of the massive sulfides hosted in the meta-sediments suggests that they were not directly formed by gravitational settling of the overlying disseminated sulfides. Interestingly, the massive sulfides at BIC have metal tenors and Cu:Ni ratios very similar to Cu poor massive sulfides at the Eagle deposit.

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Field Trip Stops

The first four stops on this trip are intended to highlight the variety of sediments that comprise the Paleoproterozoic Baraga Group in the vicinity of the BIC intrusion. They also provide an opportunity to see and discuss some of the structural complexity in this area. At stops 5 and 6 we'll examine exposures of the BIC intrusion. Stop 7 will be at the Kennecott Minerals Company core shed near Negaunee, Michigan. Here we'll have an opportunity to look at drill core form the BIC intrusion including mineralized intervals that are not exposed in the field. The location of field trip stops 1-6 are shown on figure 2. The locations of stops 5 and 6 are also shown on the more detailed BIC geology map. GPS coordinate locations provided for the stops are in UTM (Universal Transverse Mercator), zone 16. The datum is Nad 83.

All of the field trip stops, except stop 1, are in areas of privately owned surface. Permission from the surface owners is required before accessing these areas.
Some of the stops are along rivers and streams with high, often slippery banks and with potentially poor footing. Caution should be used in walking around these areas. Steep, cliff like outcrops are present in the vicinity of Stop 6, they provide great views but please stay well back from the edges.

Stop 7-1 Canyon Falls on the Sturgeon River
(UTM coordinates 386938E 5164275N)

Good exposures of the Goodrich formation quartzites are exposed along the Sturgeon River at this location. To access the area, park at the Sturgeon River roadside park on the west side of US Highway 41 and follow the marked hiking trial south about 600m to the falls overlook.

This area was a stop on a previous ILSG field trip led by Bill Cannon and John Klasner in 1972. The following stop description is an excerpt from that field guide.

"This stop illustrates an anomalous structural style in that the rocks are relatively nonfolded as compared with the deformation style of nearby Precambrian X metasedimentary rocks, Here the quartzites, composed of quartz grains in a clay matrix with chlorite porphyroblasts, show very gentle N 70º W trending monoclinal folds. Ripple marks and sole marks are common on bedding surfaces. The more argillaceous layers show the development of a N 70º W cleavage"

Ojakangas (1994) has correlated the thinly layered quartzite at this location with the Goodrich formation.

Stop 7-2 Conglomerates on top of the Bijiki iron formation near the Taylor Mine.
(UTM coordinates 388973E 5168500N)

The stop is at rubble (subcrop) along the north side of a small drainage into Ogemaw Creek about 30m southeast of Old Hwy 41 (note: Old hwy 41 from the turn off of US highway 41 to the Taylor mine turnoff is a poorly maintained road that is often rutted and muddy and occasionally flooded.

Klasner (1972) mapped a horizon of poorly exposed conglomerate and greywacke along the top of the Bijiki banded iron formation at this location. The reddish sandstone contains scattered matrix supported clasts of chert up to 10cm across. Drilling by Kennecott a few km to west of this location suggests that the Bijiki iron formation rapidly increases in thickness to the west. Perhaps, these conglomerates are additional evidence of a higher energy environment associated with the formation of a fault controlled sub-basin to the west.

Stop 7- 3 Taylor mine site
(UTM coordinates ~ 389660E 5169000N)

The Taylor Mine site can be accessed by walking east from old hwy 41 along the old Taylor mine road. A trail to the north, along an old rail grade just before the old Taylor mine pit, leads to several good bedrock exposures.

The Taylor Iron Co. shipped 32,970 tons of iron ore from the Taylor mine between 1880 and 1883 (Lake Superior Iron Ore Association, 1952). The property was explored by Ford Motor Company for iron ore during the 1950's and 1960's**.** Additional drilling was carried out on the property in the 1970's as part of a regional uranium exploration program. John Klasner (1972) produced a detailed map of the mine area as part of his Ph.D. dissertation at Michigan Technological University. Kennecott acquired mineral title to the property as part of the purchase of all of the Ford Motor Company mineral title holdings in the Upper Peninsula.

The mine site provides good exposures of the Lower Slate and Bijiki members of the Michigamme formation and diabase dykes of the Baraga-Marquette dyke swarm. Well exposed folds also contrast with the very weakly folded quartzite at stop 1. Klasner (1972) describes the folds at the Taylor mine as "asymmetric with slight overturning to the north and a recognizable S_1 axial plane foliation. The folds have an amplitude of 400 feet (122 m) and a period of 600 feet (183 m). Minor folds are superimposed on the larger folds"

Stop 7-4 Taylor Creek (optional)
(UTM coordinates 390436E 5170300N)

Good exposures of probable Upper Slate member of the Michigamme formation are found downstream along Taylor Creek from where old hwy 41 crosses it. However, in many places the banks of Taylor Creek are very steep and rocky. Access to this stop will depend on how high spring run off water level is.

The banks of Taylor Creek at this stop are steep and the footing can be poor. Use caution when climbing down to view the exposures along the creek.

Taylor Creek is within the Falls River slice, the allocthon proposed by Gregg (1993) south of the Falls River thrust fault (see fig. 2). Deformation evident in the bedrock exposures along Taylor Creek is different than that seen at either the Taylor mine or further north in the Baraga basin. In Taylor creek, small scale folds, where visible, are often nearly recumbent. In pelitic horizons, S_1 foliations typically dip gently southward and are affected by a well developed crenulating cleavage associated with a second generation of folds.

Stop 7-5 Exposures of the Lower and Middle Units on the west end of the BIC intrusion
(UTM coordinates 396027E 5174514N)

The west end of the BIC intrusion is accessible by hiking eastward from the Indian road along a series of old logging trails. The best exposures are located just below the top of the hill. **The surface and mineral title are held by Kennecott Minerals Company at this stop and permission is required to access the area.**

At this stop, a natural flat terrace on the west facing slope of the prominent hill held up by the BIC intrusion, marks the unexposed contact between the Lower and Middle units of the BIC intrusion. Outcrops down slope from the terrace are comprised of rocks that range in composition from feldspathic werhlite to olivine melagabbro. They contain minor disseminate pyrrhotite, chalcopyrite and pentlandite. Nearly complete replacement of plagioclase by secondary minerals makes accurate determinations of modes very difficult in most hand samples of this unit. The Lower Unit of the BIC intrusion is compositionally similar to the olivine rich melagabbro that hosts much of the mineralization at the Eagle Ni-Cu-PGE deposit in the eastern end of the Baraga basin.

Exposures upslope from the terrace are of equigranular, locally ophitic textured gabbros of the Middle unit. Unlike the Lower unit, neither olivine nor orthopyroxene appear to be present in the Middle unit. Minor pyrite and chalcopyrite are found as disseminations through out the unit. Hematite locally coats plagioclase giving it a pinkish hue.

The contact between the olivine rich Lower unit and the olivine free Middle unit is relatively sharp. It is currently unclear if the change represents closed system fractionation or multiple pulses of different magmas. There is currently no recognized analog for the BIC intrusion Middle or Upper units at Eagle.

More detailed descriptions of the units at BIC can be found in the first part of the guide.

Stop 7-6 Upper Unit exposures on the east end of the BIC intrusion.
(UTM coordinates 397013E 5174477N)

The east end of the BIC intrusion is accessible by a series of logging and drill roads starting off the Silver River road north of the intrusion. The last part of the road to the top of the hill is typically deeply rutted and often not drivable. Walking the last part is recommended. **Permission from Kennecott Minerals Company is required before accessing this stop.**

Glaciated exposures of the medium to coarse-grained oxide gabbro that comprise the Upper unit of the BIC intrusion are present in, and alongside the drill road going up the eastern end of the hill. Exposures of the gabbro near the top of the hill contain football size and shape patches with intense epidote alteration. The boundaries of the intensely altered rock are very sharp. It is currently uncertain if these are intensely altered xenoliths or cross sections of sub-parallel “pipe like” zones of hydrothermal alteration.

Stop 7-7 Kennecott Minerals Company core shed.

The Kennecott core shed is located 2.6 miles east of the town of Negaunee. Turn north off of US Highway 41 at the blue TV 6 building (across from the Michigan Police post) on to the old airport road. Follow the road around the curve to the west and proceed through the gate. The core buildings are the long sheds on the south side of the road just past the gate.

Core from the BIC and Little BIC intrusion will available for viewing and discussion.

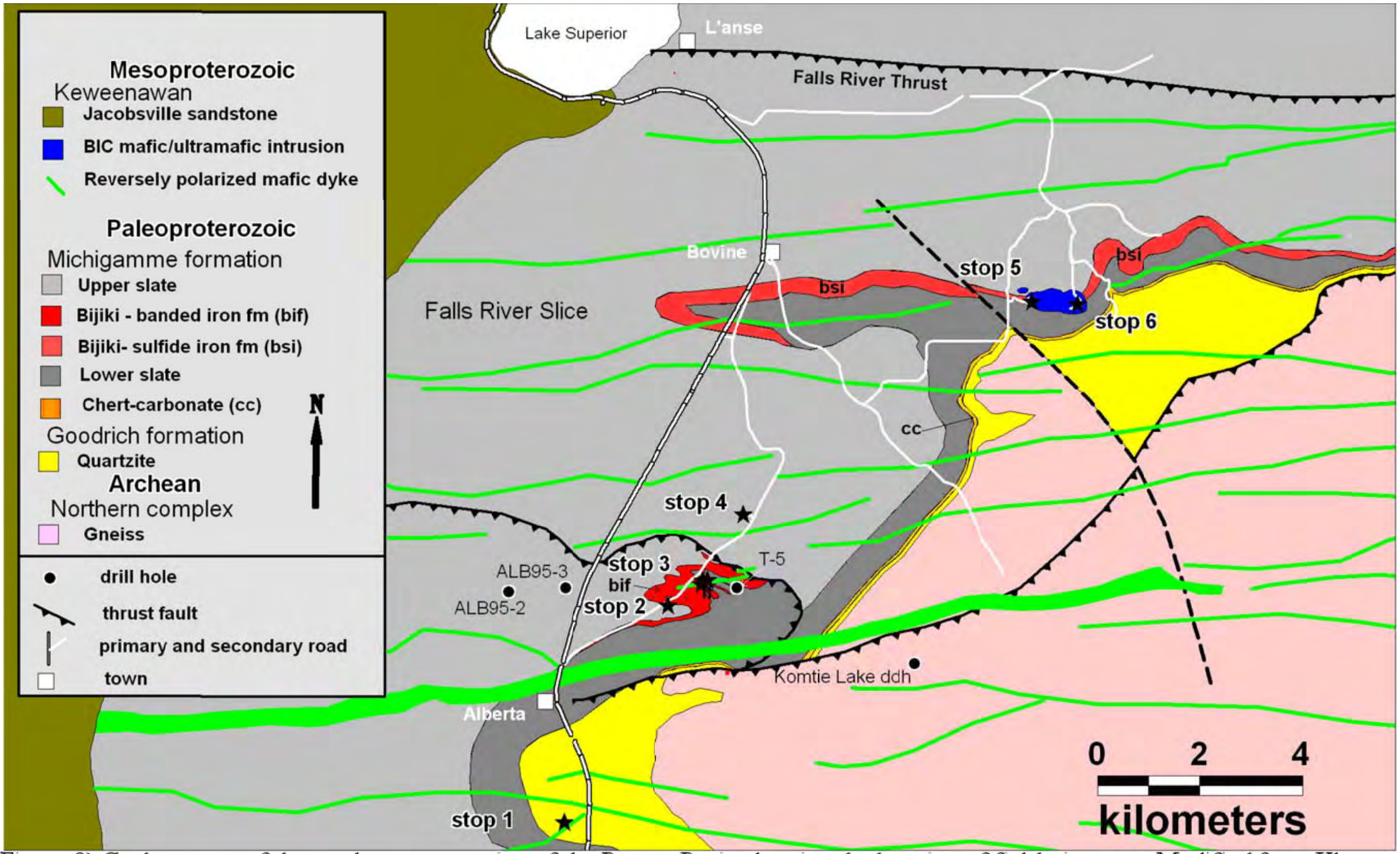

Figure 2) Geology map of the southwestern portion of the Baraga Basin showing the location of field trip stops. Modified from Klasner (1972), Klasner and others (1991) and Cannon (1977)

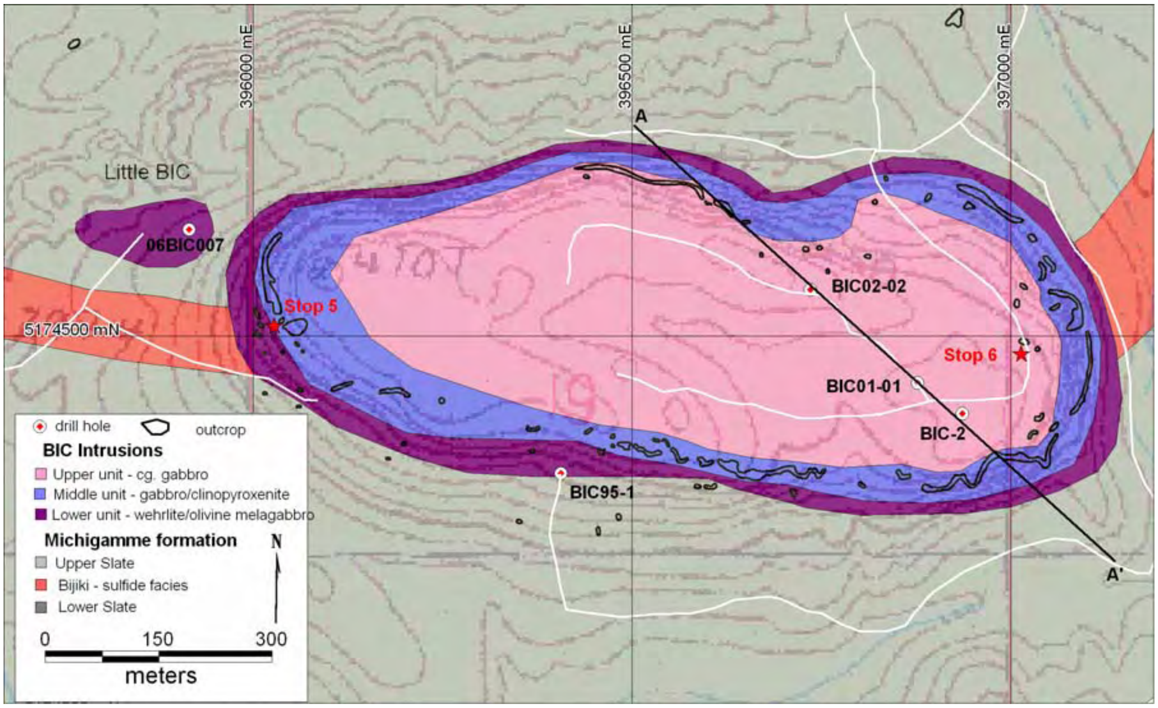

Figure 3) Geology map of the BIC intrusion showing the location of field trip stops 7-5 and 7-6.

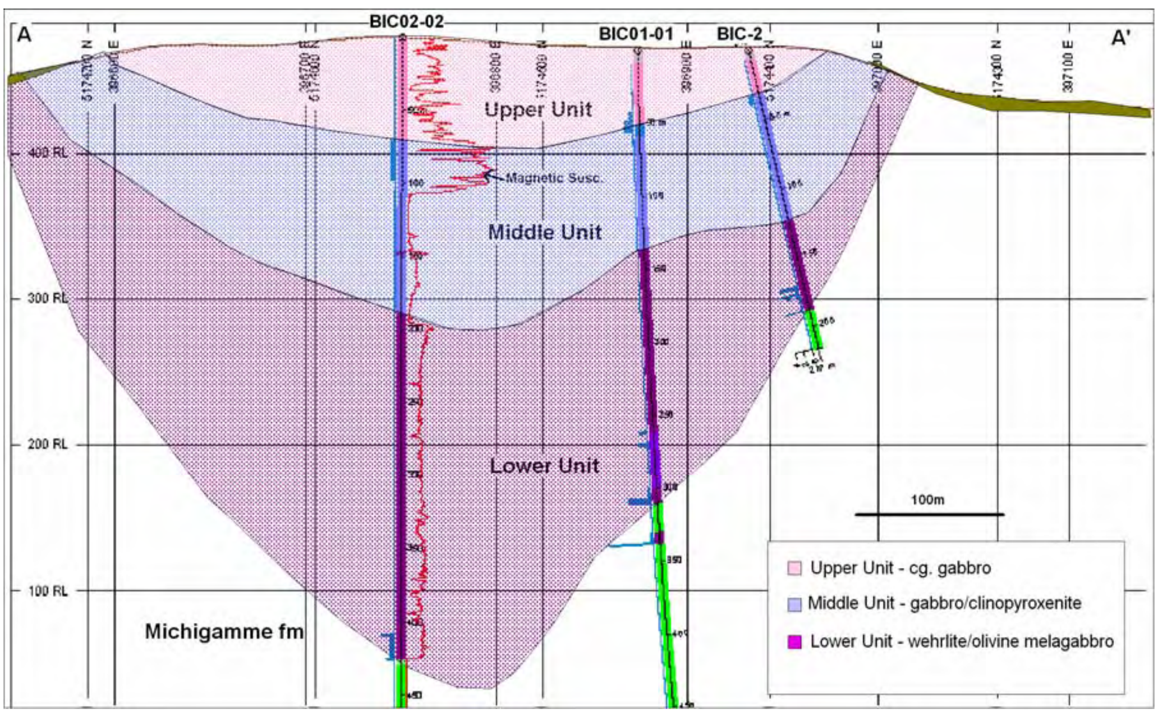

Figure 4) BIC intrusion cross-section A to A'