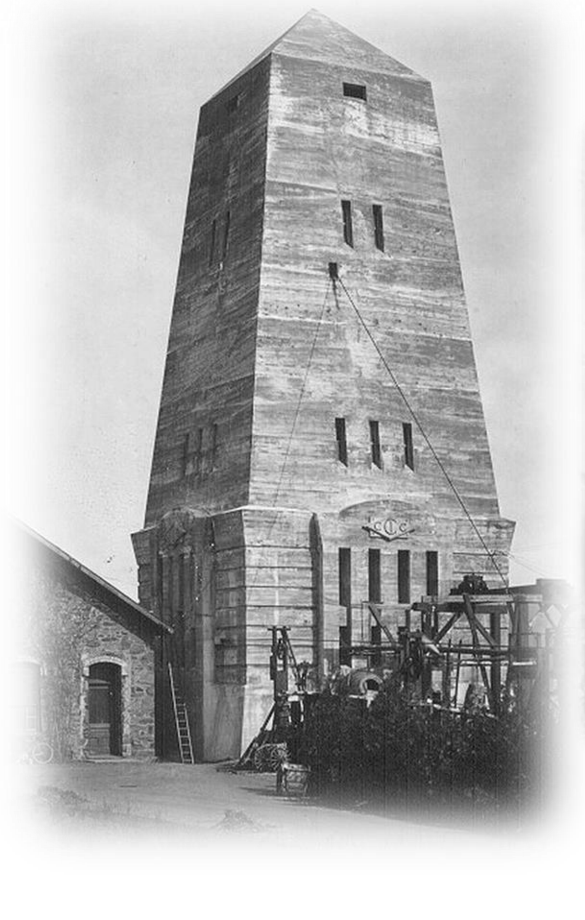
Laurentian University Society of Economic Geologists student chapter

Fall Reading Week Field Trip to the Upper Peninsula of Michigan: Marquette Iron Range and Keweenaw Copper Country



October 8th-14th, 2017

Field Guide

Organized by Dylan J. McKevitt and LU-SEG Executive Committee

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List of Participants

Name	Citizenship	Position
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Gerald Broughton	Canada	B.Sc. student
Kevin Baloyi	South Africa	M.Sc. student
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Xuyang Meng	China	Ph.D. student
Will McNeice	Canada	M.Sc. student
Danielle Shirriff	Canada	M.Sc. student
Ijaz Ahmad	Pakistan	Ph.D. student

Sponsors and Hosting Companies

Itinerary

Sunday, October 8, 2017

- Morning: Drive from Sudbury, ON to Sault Ste. Marie via Hwy 17. *3hr30min*
- Afternoon: From Sault Ste. Marie, south on I-75, then west on M-28 to Munising. *2hr00min*
    - Take East Munising Avenue (H-58) east out of town; continue on Adams Trail; turn left on Miners Castle Road. *00hr15min*
    - Pictured Rocks National Lakeshore, Miners Castle. *2hr00min*
- Drive back to Munising, and west on M-28, to US-41 to Marquette, MI. *1hr05min*
- Night in Marquette.

Monday, October 9, 2017 (Canada Thanksgiving!)

- Morning: Outcrops around Marquette, Negaunee. Museums.
    - Mount Mesnard overlook. (Head south on US-41; turn right on Cliff Power Rd just before the water treatment plant, and right again on Marquette Rd).
    - Kona Dolomite near Harvey Quarry. (Backtrack to US-41, head south; park at MI Welcome Center).
    - Pillowed Basalt along US-41. (Head west from Marquette on US-41; across from Shunk Furniture, park along right side of road)
    - 11:00 AM: Michigan Iron Industry Museum. *1hr30min*
- Lunchtime: Miners Park, Negaunee. *2hr00min*
    - Look at roadcuts near Ferrell Gas and Fox Motors.
- Afternoon: Outcrops in Ishpeming, Negaunee.
    - Kitchi Creek Schist agglomerate along Deer Lake Rd.
    - Jasper Knob.
    - Little Mountain Mine.
    - North Jackson Mine in Negaunee.
- Evening: Thanksgiving dinner at Presque Isle Park, Marquette. Walk around Presque Isle, view outcrops, ore docks.
- Night in Marquette.

Tuesday, October 10, 2017

- Morning: CR 510 Dead River Bridge outcrop.
- Afternoon: tour of Cliff's Tilden open pit iron mine. *2-3hr00min*
- Evening: fill-in with missed outcrops from yesterday.
- Night in Marquette.

Wednesday, October 11, 2017

- Morning - afternoon: surface tour of Lundin's Eagle Mine, visit to Exploration Office, visit to Humboldt Mill.

- Drive to Houghton, MI. *1hr30min (from Humboldt)*
    - En Route: Champion Mine rock pile.
- Night in Houghton.

Thursday, October 12, 2017

- Morning: tour of Quincy Mine. 1-2hr + self-guided surface tour (*1hr30min?*)
- Afternoon: Seaman Mineral Museum. *2hr00min*
- Night in Houghton.

Friday, October 13, 2017

- Morning: Drive north on US-41 towards Eagle River, then Copper Harbor. *1hr20min*
    - Outcrops and collecting at rock piles.
- Afternoon: Driving north then east on M-26 (leave US-41 at Phoenix).
    - Outcrops. Estivant Pines near Copper Harbor.
- Evening: Brockway Mountain Drive at sunset.
- Night in Copper Harbor.

Saturday, October 14, 2017

- Morning: Leave Copper Harbor for Sudbury, via Sault Ste. Marie. *9hr30min*
- En route: Stop at Prospector's Paradise rock shop.

Introduction

This guidebook has been produced to accompany the Laurentian University Society of Economic Geologists student chapter's annual fall reading week field trip. This year, the executive committee chose to travel somewhere "new" that most students at Laurentian's Harquail School of Earth Sciences had not experienced. An obvious choice that combined a mix of historic and present-day mining with diverse ore deposit styles, and accessible within a day's drive, was Michigan's Upper Peninsula. Since the trip organizer (DJM) was raised in the Negaunee area, making contacts and planning logistics was relatively simple.

This guidebook liberally draws upon many open-source publications, journal articles, and personal communication with local experts. The author has tried to accurately reference all sources; however, some mistakes surely persist. Thus, this guidebook will be reviewed and edited as time allows.

The trip is broken into two parts; the Marquette Iron Range, and the Keweenaw Copper Country. Within this guide, each part features a description of the regional geology followed by regional (mining) history, and finally stop descriptions organized by day. As this is the first "trial" run of this trip, specific stops and their sequence are subject to change.

We would like to thank the trip participants for expressing interest and thereby making this possible. Also, we extend sincere gratitude to: the Harquail School of Earth Sciences (including Doug Tinkham, Tobias Roth, and Roxane Mehes) for providing supplies and help with securing funding; Lukas Lundin and the Lundin Mining Corporation, who provided financial support to visit the Eagle Mine; Cliffs Natural Resources and Al Strandlie at the Tilden Mine; Bob Mahin and Meagan Morrison at Eagle Mine; Ted Bornhorst and Robert Barron (Michigan Tech University and A.E. Seaman Mineral Museum) for assistance in planning and securing stops along the Keweenaw; Tom Waggoner (retired geologist) and Dick Ziegler (Northern Michigan University) for help with stops in the Marquette-Negaunee-Ishpeming area; and Troy Henderson for guiding our visit to the MI Iron Industry Museum.

There's a classic adage: *"The best geologist is the one who's seen the most rocks."* To that, I'd add *"… and who's shared precious time to pass on their expertise."* In that case, I've had the privilege of meeting many great geologists in the course of this trip, and I hope we can faithfully pass it forward in return.

Cheers,

-DJM, and the LU-SEG 2017 Executive Committee

October 7, 2017

Part 1: The Marquette Iron Range

Regional Geology *(Descriptions largely from Bornhorst & Klasner, 2008)*

The Paleoproterozoic Marquette Range Supergroup consists of three groups (the Chocolay, Menominee, and Baraga). Due to Penokean-related and younger plate tectonic activity, they have been folded and faulted down into underlying Archean basement, yielding gently west-plunging (Marquette Trough) or northwest-plunging (Republic Trough) synclines. (Fig. 1)

The following is the abstract from: Tinkham, D.K. and Marshak, S. (2004) *Precambrian dome-and-keel structures in the Penokean orogenic belt of northern Michigan, USA*. GSA Special Papers 2004, v. 380, p. 321-338.

The Penokean orogen of Michigan's Upper Peninsula includes a belt of dome-and-keel structure presently defined by deep troughs, or "keels," of Paleoproterozoic Marquette Range Supergroup strata between gneiss domes composed of Archean basement rock. Structural, metamorphic, and geochronological data from the Southern Complex indicates that dome-and-keel structure developed in two stages. The first stage involved rise (intrusion, possibly diapirically) of the 2.6 Ga Bell Creek Assemblage (a gneissic megacrystic granite) into the Twin Lake Assemblage (migmatitic mafic to felsic gneiss). Flow folding in gneisses and migmatites indicate that this Archean event involved plastic flow of basement. The second stage occurred after the ca. 1.8 Ga Penokean orogeny, subsequent to the formation of a fold-thrust belt involving Paleoproterozoic Marquette Range Supergroup strata. During this stage, deep, narrow troughs developed in the region that had been the fold-thrust belt. Analysis of structures bordering the Republic Trough

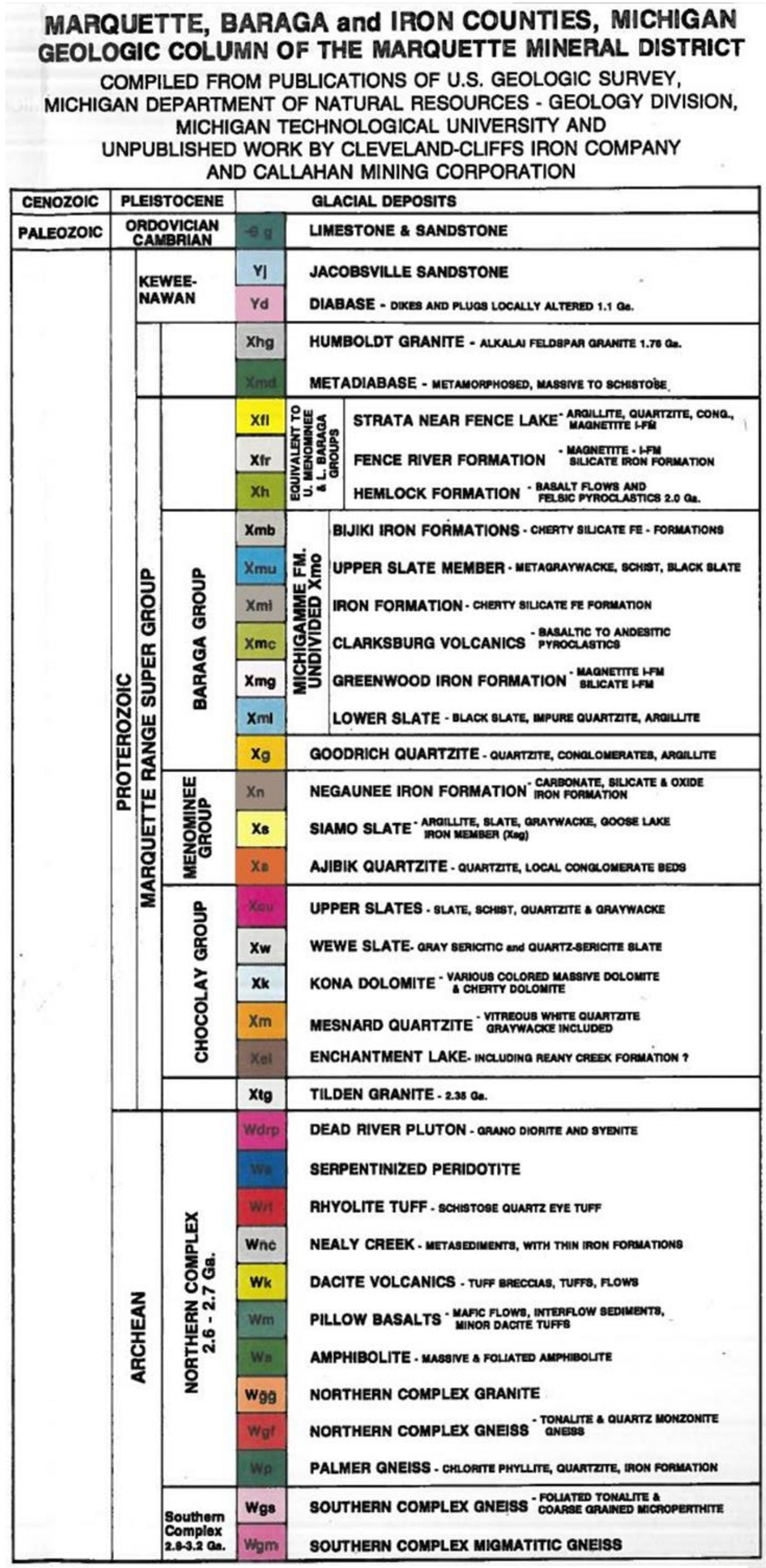


Figure 1: Stratigraphic column for the Marquette Iron Range area.

indicates that Paleoproterozoic keel borders are shear zones; keel rocks moved down relative to dome rocks. In effect, the Paleoproterozoic keels are steep- to vertical-sided grabens, suggesting that the dome-and-keel architecture is a consequence of extensional faulting. Amphibolite facies metamorphism occurred in Paleoproterozoic keel strata along dome-keel borders. Peak-metamorphism developed adjacent to dome borders at the time keel-bounding shear zones were active. The relative timing of Paleoproterozoic keel formation supports the model that this stage reflects collapse of the Penokean orogen. Our results show that the present dome-and-keel structure of the Southern Complex region represents superposition of Paleoproterozoic collapse structures on preexisting Archean gneiss domes.

The Chocolay Group consists of a basal conglomerate with overlying quartzites, carbonates, and slates. It contains the basal Enchantment Lake Formation progressively overlain by Reany Creek Formation, Mesnard Quartzite, Kona Dolomite, and Wewe Slate. The Enchantment Lake Formation features a conglomerate with clasts of the underlying lithology (Archean), and the depositional environment has been interpreted as glacial (with dropstones) or in alluvial fans. Mesnard Quartzite is typically massive and white with numerous ripple marks, clasts, and local cross-bedding.

Kona Dolomite consists of approximately 48% dolomite, 42% argillite, and 10% quartzite. Sedimentary (algal mats, ripple marks and mud casts) and replacement features suggest a shallow, saline lagoonal or open tidal depositonal environment. Bladed or fibrous chert rosettes, nodular quartz and cubic-rectangular bright red dolomite crystals indicate replacement of gypsum, anhydrite, and halite. The Kona displays a variety of stromatolites (as large bioherms or small thin undulating mats). It also hosts strata-bound copper sulfides which have attracted exploration interest since 1888, with an indicated resource of 0.5 billion short tons of argillite/quartzite containing about 1% Cu. Sulfides (chalcopyrite, bornite, chalcocite) occur as disseminated grains or grain aggregates and shear zone fillings. Sulfides show a decrease in copper from east to west. The occurrence of sulfides within carbonate cement indicates mineralization contemporaneous with dolomitization and lithification (Bornhorst & Barron, 2011). The deposit model infers copper-bearing fluids moving through the middle quartzite layer and upward / downward into adjacent argillite beds. The Kona Dolomite deposit is best classified as a reduced-facies sediment-hosted copper deposit. (Fig. 2)

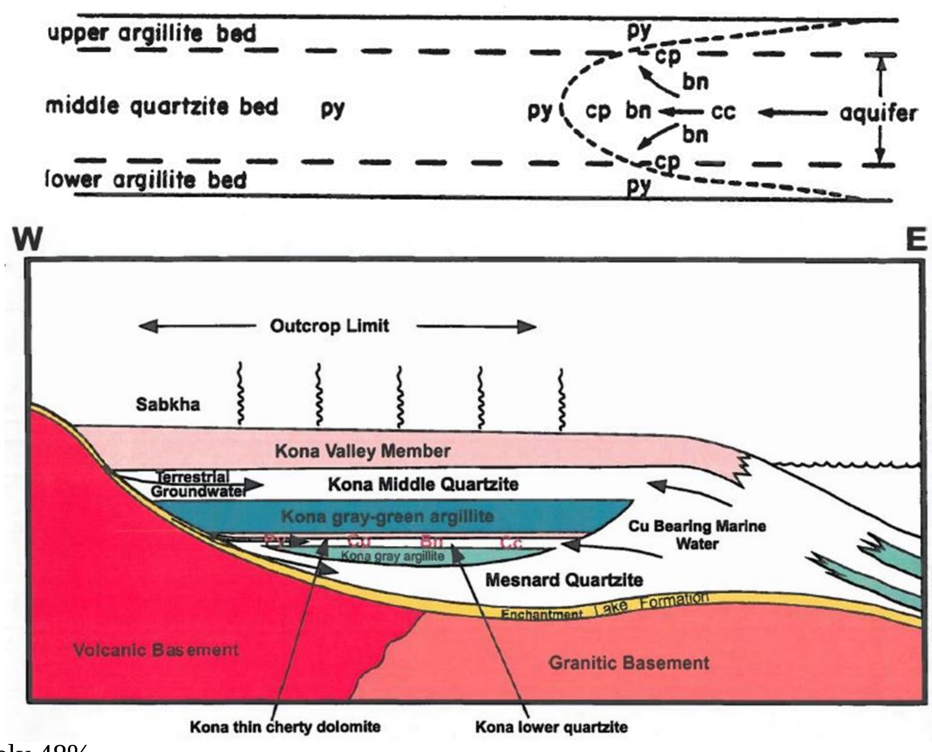


Figure 2: Mineralization model for Kona Dolomite-hosted sulfides. From *Phelps Dodge Exploration Annual Meeting and Workshop, 2005: Copper Deposits of Western Upper Peninsula* by *Theodore J. Bornhorst.*

The fine-grained and laminated fissile Wewe Slate argillite ranges in thickness from 400-3000 feet. Some zones contain 2-5% disseminated pyrite. Outcrops are very limited.

The Menominee Group features alternating slates and quartzites with minor banded iron formation (BIF), overlain by the rich Negaunee Iron Formation. The basal Ajibik Quartzite is generally pure with minor greywacke and ranges from 450-600 feet thick. It unconformably overlies the Wewe Slate, and locally features a basal conglomerate containing jasperoid (silicified Kona Dolomite) and schist clasts, suggesting that hydrothermal alteration started before the Ajibik, while quartz/hematite stockworks that transect and cause brecciation in the Ajibik suggest a long-lived stockworks zone lasting until after the Negaunee Iron Formation.

The Siamo Slate conformably overlies the Ajibik and ranges from 1000-3100 feet thick. It contains slate and lesser greywacke and feldspathic quartzite, along with an up to 100-foot-thick iron formation (the Goose Lake member, the first iron formation in the Marquette trough). The transition from upper slate with chert bands to overlying Negaunee Formation is gradational.

The Negaunee Iron Formation is one of many iron formations within the much larger Paleoproterozoic Animikie basin (found in parts of Wisconsin, Minnesota, Michigan, and Ontario). Together, these banded iron formations are known as Lake Superior Type (LST). They stand in contrast to smaller Algoma Type iron deposits. Traditionally, LST was thought to have very limited igneous association in contrast to Algoma Type; however, recent views suggest LST may also have significant igneous input (e.g., extensive extrusive rocks in the Animikie Basin – Hemlock, Clarksburg, and Emperor volcanics). Other differences include age (LST at 1.8-2.4 Ga, Algoma at >2.5Ga), environment (LST – rifting, Algoma – volcanic arc), concentrations of S-Na-K-Al-P (LST – low, Algoma – high), and CO2 (LST – higher, Algoma – lower).

Worldwide research on the origin of this deposit type has been strongly influenced by ore deposit models from the Lake Superior region. Arguments still persist over the importance of various mineralization processes (dissolution-precipitation by meteoric fluids, ascending magmatic fluids, or gravity-driven large-scale groundwater flow during tectonic uplift). However, an inability to date high-grade hematite ores has hindered the testing of competing models. Recent work (Rasmussen, Zi, Sheppard, Krapež, & Muhling, 2016) suggests the formation of high-grade hematite orebodies in the Marquette Iron Range involved up to three events. Depositional age of the lower part of the Negaunee Iron Formation is constrained to before 1.89 Ga by a dated mafic intrusion. As evidenced by pebbles of hematite ore in overlying Goodrich Quartzite basal conglomerate, and an ejecta layer in the lower Michigamme Formation, the first mineralization episode occurred after deposition and initial deformation of the Negaunee Iron Formation but before the 1.85 Ga Sudbury impact event. A second phase of enrichment is recorded within the hinge of Penokean-aged folds (1.8 Ga). A third phase of later upgrading is recorded in the limbs of regional folds (1.77 Ga). These ages suggest multistage mineralization processes linked to orogenic events (here, the Penokean Orogeny at 1.87-1.83 Ga and the Yavapai-internal accretion which reactivated Penokean structures during 1.78-1.75 Ga) are key to the formation of high-grade, Lake Superior Type hematite orebodies. In general, the recrystallized hard ore coarsens with increasing metamorphic grade to the west, implying a temporal link to regional metamorphism. It appears that progressive upgrading to high-grade hematite deposits requires repeated episodes of structurally- and stratigraphically-controlled fluid flow.

The Negaunee Iron Formation is extremely variable over short distances, indicating variations in iron source, transportation, depositional environment, diagenetic alteration, and metamorphic grade. Present-day mineralogy may not reflect original minerals: for example, stilpnomelane and minnesotaite (common silicates in the eastern Marquette trough) may be transformed with moderate heat and pressure to cummingtonite or grunerite (present in Negaunee IF near diabase sill intrusions). Sodium-rich zones contain riebeckite and acmite, likely the result of early diagenesis or low-rank metamorphism. The majority of magnetite and martite ore was originally carbonate-silicate-chert (remnants found at the Tilden and Empire deposits). Most magnetite grains were originally very fine hematite that was altered to magnetite under a reducing diagenetic environment. Also present is supergene oxidation and enrichment of carbonates, silicates and magnetite to hematite, goethite and martite. However, certain clays (e.g., dickite and high-Cr nontronite) suggest a hydrothermal input rather than near-surface weathering. Clearly, many processes (both primary and secondary) have controlled mineralization styles along the Marquette Iron Range; for further discussion, see Banded Iron Formation of the Marquette District by T. Waggoner, in Bornhorst & Klasner (2008).

For a recent discussion linking rapid crustal growth with 1.88 Ga iron formations, considering Archean and Proterozoic iron formations in context of global hydrospheric and atmospheric conditions, see Rasmussen et al. (2012).

The Menominee Group also includes Hemlock Volcanic Formation from the Amasa Oval, where waning volcanism emplaced an overlying iron formation. The Hemlock Volcanics exceed 10,000 feet in thickness and are centered on the Amasa Oval southwest of the end of the Marquette Trough, yet they thin rapidly eastwards and are not notably present in the Ishpeming-Negaunee-Marquette area. Immediately overlying iron formations are laterally-equivalent with the Negaunee Iron Formation; thus, the Hemlock volcanic event may have provided minerals and heat for Negaunee mineralization. (Bornhorst & Klasner, 2008; Rasmussen et al., 2016)

The Baraga Group contains the basal, 300 to 1400-foot-thick Goodrich Quartzite (some of which has been mined for hard ore of Fe-rich conglomerate with hydrothermally-emplaced hematite: Hard Ore Mine in Ishpeming, Republic Mine, and Goodrich Mine). The overlying Michigamme Formation (11,000-20,000 feet thick) features a Lower Slate Member (locally phosphate enriched to >15% P_2O_5), Greenwood Iron Formation Member, Clarksburg Volcanic Member, a Middle Greywacke/Slate Member, the Bijiki Iron Formation Member (100-200 feet thick, primarily limonite ore mined west of Lake Michigamme), and the Upper Slate Member. Metamorphism of the Michigamme near the Baraga/Marquette County line has produced quartz-biotite garnet and staurolite schists.

Keweenawan diabase dikes outcrop throughout the Marquette Iron Range. Whereas some older non-Keweenawan intrusives control enriched ore occurrences, these do not, yet they are altered by solutions acting in the porous oxidized and enriched zones.

Regional History

This section heavily references Banded Iron Formation of the Marquette District by T. Waggoner, in Bornhorst & Klasner (2008).

The mineral potential of Michigan's Upper Peninsula was first discovered in 1844, when U.S. deputy surveyor William Burt (working for geologist Douglass Houghton) explored the U.P. and found a rich vein of iron ore with his "spinning" magnetic compass. The following year (1845), Philo M. Everett was shown boulders of Fe-ore under the roots of a fallen pine tree by Chippewa Chief Marji-Gesick. This was the beginning of an "iron rush" as companies quickly formed and sought to raise capital.

Mining started in 1848. Early on, it focused on surface outcrops of Negaunee Iron Formation hydrothermal hematite and magnetite ores (hard ore). Production was slow due to poor transportation systems. Local charcoal furnaces produced pig iron using charcoal produced from the local forests. Railroads were soon built and boat locks installed at Sault Ste. Marie in 1855; this allowed passage of large lake vessels from Lake Superior to the lower Great Lakes where production of raw iron ore increased at the lower lake steel mills.

Underground mining in the later 1800s opened shallow supergene-enriched hematite (soft ore) for production. By the mid-1900s most deposits were depleted. This fueled intense research and development in the 1950s resulting in new concentration schemes for banded iron formation. Previously, this lower-grade material was mined and shipped as siliceous ore for use in furnaces to provide adequate slag production; now, it yielded an iron concentrate/pellet with relatively low silica and superior physical and chemical characteristics to improve furnace productivity.

On the Marquette Range, the first concentrating/pellet operation was at the Humboldt Mill (now used by the Eagle Mine) in 1954, followed by the Republic Mine in 1956. Hematite was concentrated through multiple methods; anionic hot oil flotation (Republic and Humboldt Mines), magnetite separation (Empire Mine), and cationic silica flotation (Tilden Mine). Thomas A. Edison, in the late 1800s, invested in and invented electromagnetic separation and roll-crushing; although he went broke on his mining and concentrating activities, his operations persisted and are integral to present-day iron ore processing.

The last operating underground hard ore mines (Cliffs Shaft and Champion Mine) closed in 1967-1968. The last underground soft ore mine stopped in 1972 (Mather B). The last siliceous, the Old Tilden Mine, shipped its final load in 1973. The Humboldt closed in 1974 (exhausted ore), and the Republic Mine finished in 1981 (difficult economic circumstances).

Iron mining lives on today along the Marquette Iron Range through Cliffs Natural Resources' open pit Tilden Mine (its sister – the Empire Mine – was closed in 2016).

The Eagle Intrusive Complex

(The following heavily references Field Trip 4: Geology of the Eagle Project by A. Ware, J. Cherry, and X. Ding, in (Bornhorst & Klasner, 2008).)

Lundin Mining Corporation's Eagle Mine was originally drilled by Kennecott Mineral Company in 2001, and found to contain disseminated and massive magmatic Cu-Ni sulfides. The Eagle intrusion and associated abundant mafic dikes is part of the 1.1 Ga Midcontinent Rift System, whose volcanic rocks (mostly tholeiitic with some intermediate and rhyolitic rocks) are exposed around Lake Superior (including along the Keweenaw Peninsula) but not in the Eagle area.

Differing from the related Duluth Complex (Minnesota) and Mellen Complex (Wisconsin), Eagle mineralization is distributed throughout the host chonolith rather than restricted to basal contacts. The Duluth and Mellen represent low grade but high tonnage resources; the Eagle hosts much higher Cu, Ni, and PGE ore tenors. These features, along with more olivine and a lack of layering suggest the Eagle intrusion was a dynamic magma conduit similar to the Voisey's Bay feeder dike in Labrador.

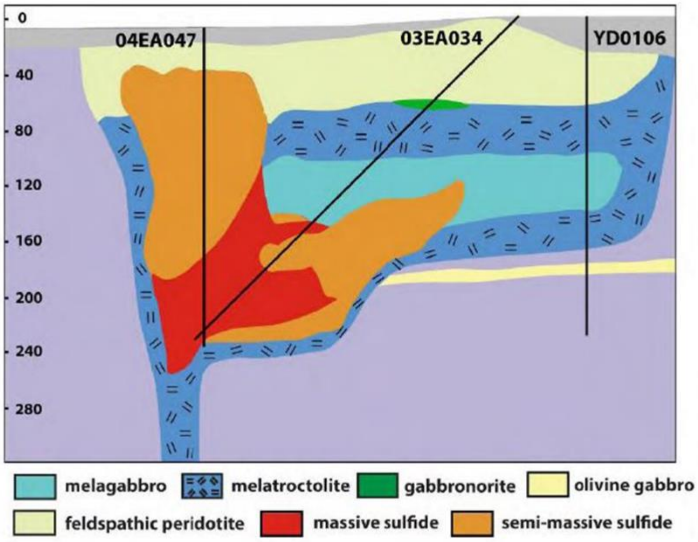
The Eagle ultramafics intrude into Michigamme Formation of the Baraga Group sediments in the Baraga Basin. See Figures 3-4 for lithologies and geometry of the intrusion. Note the main ore reserve comprises two semi-massive massive sulfide zones linked by a massive sulfide zone. Mineralogy is typical of magmatic sulfides: pyrrhotite, chalcopyrite, pentlandite, 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. Trace amounts of Co, Ag, and Au are also present.

Whole rock and mineral geochemical analyses suggest contamination at depth and multiple magma pulses (of at least three parental magmas) from a staging chamber are responsible for the Eagle deposit.

(The following references "Eagle Mine – a subsidiary of Lundin Mining," n.d.)

Eagle Mine is an underground (utilizing long-hole stoping), high-grade Ni-Cu mine. It is the first mine to be permitted under Michigan's Part 632 Non Ferrous Mineral Mining Law (passed in 2004).

Surface construction began in 2010, with underground construction in 2011. In 2012, refurbishment and construction at the Humboldt Mill began. 2013: Lundin Mining Corporation purchased Eagle from Rio Tinto (Kennecott). Production began in 2014, and by 2015 was a 24/7 operation processing approximately 2,000 metric tons of ore per day.



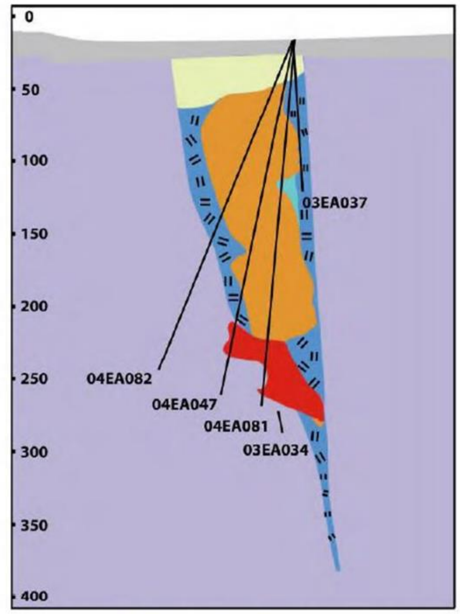


Figure 3: Eagle deposit lithologies and geometry shown by long sections. From Field Trip 4: Geology of the Eagle Project by A. Ware, J. Cherry, and X. Ding, in (Bornhorst & Klasner, 2008).

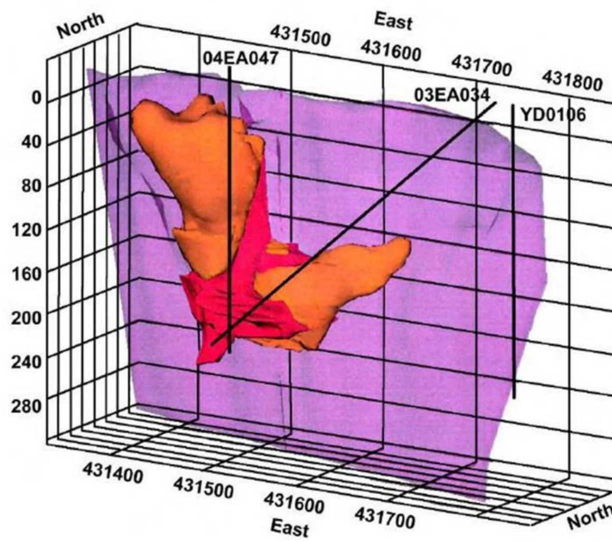


Figure 4: Eagle main deposit block diagram showing ore distribution. Red is massive sulfide; orange is semi-massive. Vertical and horizontal scales in meters. From Field Trip 4: Geology of the Eagle Project by A. Ware, J. Cherry, and X. Ding, in (Bornhorst & Klasner, 2008).

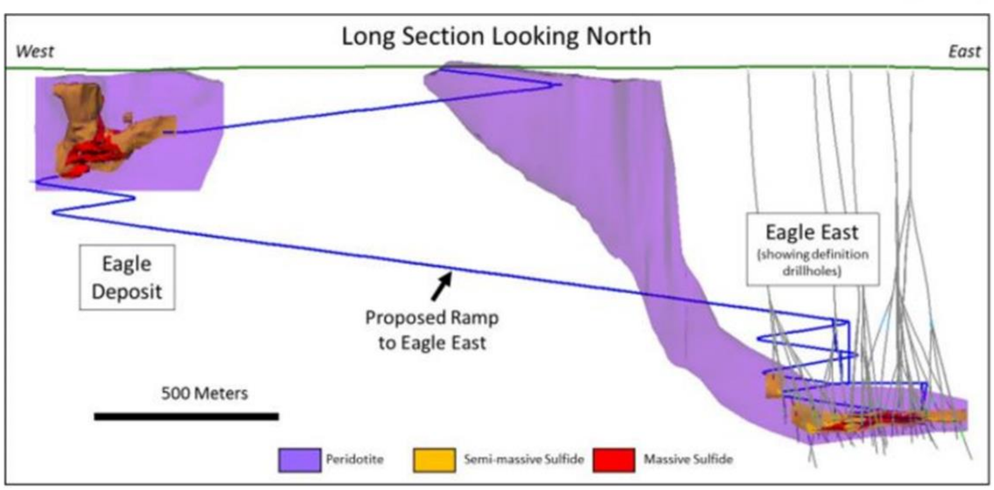


Figure 5: Long section through the main Eagle and recently-discovered Eagle East deposits. From an April 10, 2017 press release: http://eaglemine.com/eagleeast/.

The mine is expected to produce 365 million pounds of nickel, 295 million pounds of copper, and trace amounts of other minerals over its estimated eight year mine life (2014-2022). Between 2011 and 2025, Eagle Mine's direct and indirect impact is estimated to generate an additional $4.3 billion for Michigan's economy. Eagle Mine will supply 1.5% of the world's nickel.

On April 10th, 2017, Lundin Mining Corporation released the results of a feasibility study for the recently-discovered Eagle East orebody (Fig. 5). Highlights include:

- An updated Mineral Resource estimate comprising 1.29 million tonnes classified as Indicated grading 5.2% Ni and 4.2% Cu and an additional 0.29 million tonnes of Inferred grading 1.7 % Ni and 1.4% Cu.
- The Feasibility Study indicates that these Mineral Resources can be mined with no significant changes to the current mine, ore transport, mill, and tailings infrastructure.
- Similar mining methods to Eagle are proposed and a maiden Probable Mineral Reserve of 1.54 Mt at 3.7% Ni and 3.0% Cu has been estimated. Mining of this Mineral Reserve will significantly increase nickel and copper production from 2020 and extend estimated mine life to at least 2023.

Cliffs Natural Resources' Tilden Mine

(The following is taken with only minor modification from Field Trip 6: Sustainable Recovery of Iron from the Marquette District by G. Scott, H. Lukey, A. Strandlie, and CCI/CCMO staff, in Bornhorst & Klasner, 2008.)

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. 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, the recently-closed Empire mine, and the presently operating Tilden property.

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 (as of 2008) 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.

The Tilden is located on the southern margin of the trough and are in fault contact with the Archean gneiss terrane. Local structure consists of upright to steeply inclined second order anticlines and synclines with low angle northwest and southwest plunges. 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.

Day 1 - Sunday, October 8, 2017: Sudbury, ON to Marquette, MI. Pictured Rocks National Lakeshore.

Driving west from Sault Ste. Marie, MI on US-41.

Heading west from the international border, we will cross over a sequence of southward-dipping sandstone, limestones, dolomites, and shales of the northern extent of the Michigan Basin sedimentary strata. The Michigan Basin is centered on Michigan's Lower Peninsula, with Cambrian-Ordovician sandstones and carbonates along the margin (and at depth) and Carboniferous strata (and minor Jurassic sediments) at the center. It hosts economic gypsum and halite deposits, as well as oil and gas. Although mostly obscured by a veneer of Quaternary glacial drift, pay attention to outcrops along roadcuts (especially the exit from I-75 to US-41). From Sault Ste. Marie until about halfway to Munising is progressively younger strata (from Late Cambrian to Ordovician to Early Silurian); this sequence is repeated in reverse (progressively older) until we reach Munising.

Stop 1.1: Pictured Rocks National Lakeshore – Miner's Castle overlook (534450mE, 5148980mN [NAD83])

Pictured Rocks National Lakeshore boasts 15 miles of shoreline with 50-200 ft sandstone cliffs, stained with iron (red-orange), copper (blue-green), manganese (brown-black), and limonite (white) minerals. Wind and waves have sculpted sea caves, arches, blowholes, turrets, and stone spires from the cliffs.

Late Precambrian Jacobsville Formation sandstone is the oldest rock here, rising only a few feet above lake level at the Lakeshore's easternmost end. It was quarried on nearby Grand Island (to the west) for building stone in the late 19th century; its characteristic white reduction spots make it easy to spot in old buildings across the U.P., including Munising, Marquette, and Houghton. We will see this formation in outcrop along the eastern Keweenaw Peninsula.

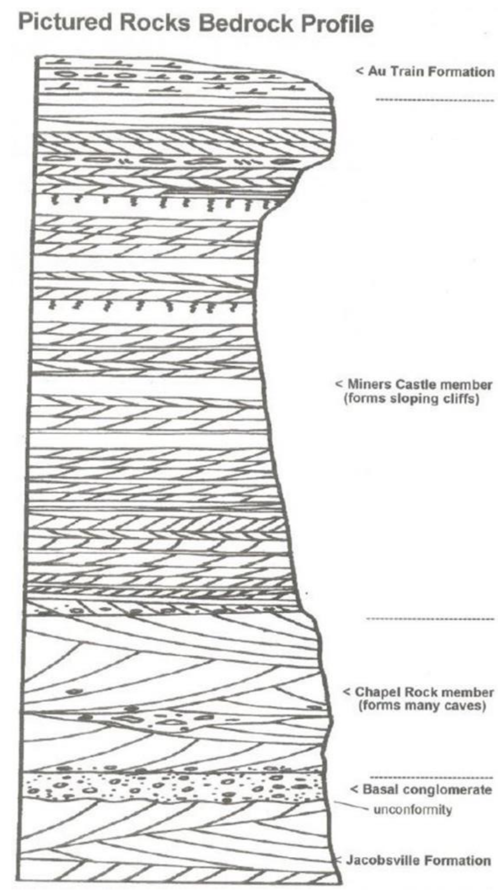


Figure 6: Stratigraphic profile through the strata exposed at Pictured Rocks National Lakeshore. From Rose' (1997).

Unconformably overlying the Jacobsville Sandstone (and exposed westward along the lakeshore) is the Mid-Late Cambrian Munising Formation. It consists of three members; a basal conglomerate, the hard Chapel Rock sandstone (with large-scale cross-bedding), and the easily eroded Miners Castle sandstone.

The resistant Early Ordovician Au Train Formation overlies the Munising Fmn and covers the western half of the National Lakeshore. This light brown to white dolomitic sandstone is the most fossiliferous along the Lakeshore – it hosts some cephalopods and gastropods. 26 conodont taxa occur in the lower Au Train Fmn and upper Munising Fmn, along with trilobite fragments in the Miners Castle member.

We will stop briefly at Miner's Castle (Munising Fmn). Jacobsville Fmn is below lake level here; the lowest exposure is of sweeping cross-beds of the Chapel Rock Member, transitioning upwards to smaller-scale cross-bedding.

(For detailed descriptions of depositional environments, see Rose' (1997); for a general overview of the Lakeshore's geology, see "Geologic Formations - Pictured Rocks National Lakeshore (U.S. National Park Service)," n.d.)

Day 2 – Monday, October 9, 2017: Marquette, Negaunee, Ishpeming area outcrops and museums.

<u>Stop 2.1: Mt. Mesnard (469126mE, 5151279mN [NAD83])</u>

After a fairly steep uphill drive, park and walk a short distance to the lookout. As you climb the last few meters, note the crampon gouges in the rock that help highlight interfingering of two formations; the Kona Dolomite is easily scratched, while the Mesnard Quartzite shows little – no marks. This relatively pure quartzite was used by Native Americans for hunting points. This stop offers a nice view of the Marquette area, including two ore docks (the newest one is farthest north), and Sugarloaf and Hogsback mountains nearly due north (composed of Compeau Creek Gneiss).

<u>Stop 2.2: Kona Dolomite near Harvey Quarry - ***No rock hammers!*** (472028mE, 5150248mN [NAD83])</u>

Park at the Michigan Welcome Center along the lake, and carefully and quickly cross US-41. On the north side of the abandoned Harvey Quarry (just south of the roadcut, by a guardrail) is beautiful exposure of Kona Dolomite. Hike around 20 meters up a narrow trail to the cliff face and view massive stromatolites.

<u>Stop 2.3: US-41 pillowed basalt (461171mE, 5153784mN [NAD83])</u>

Pull over along the east side of US-41, just across the road from Shunk Furniture. This well-known and very photogenic outcrop features pillowed basalt of the Mona Schist sequence, which as an overall thickness of nearly 5 miles and has been tilted on its side.

<u>Stop 2.4: Michigan Iron Industry Museum (456708mE, 5152165mN [NAD83])</u>

Besides excellent exhibits of the local mining history and lifestyles, a short video, and free admission (donations appreciated), this well-kept museum features a couple interpretive walking trails. We will learn about the historic, nearby Carp River forge (the first iron forge in the Lake Superior region), various mines, and even view the Empire Mine tailings piles to the south.

<u>Stop 2.5: Negaunee roadcuts and Miners Park (Lunch) (453830mE, 5151242mN [NAD83])</u>

At Miners Park, we will take lunch and also take a look at the pyramid-shaped monument commemorating the discovery of iron ore in the Negaunee area.

Just across the street (US-41), next to Ferrell Gas, is a "textbook" outcrop of what appear to be clastic quartzite dikes cutting up into Siamo Slate (see Davis, G.H., Reynolds, S.J., and Kluth, C.F. (2012) Structural Geology of Rocks and Regions, 3rd edition, page 512). Note the structural fabrics and foliation (near-vertical cleavage), and how they relate to the different lithologies. Upon closer examination, you will notice the quartzite units are parallel with bedding in the slate. Less-competent mudstone accommodated strain with formation of foliation, whereas more-competent quartzite experienced regular jointing and slip (evidenced by slickensides) along quartzite-slate contacts.

A short walk north along both sides of US-41, just past Fox Motors, is another excellent roadcut. Moving eastward (away from Negaunee), you will encounter progressively older strata: Ajibik Quartzite (historically quarried in Marquette for making whetstones, along Whetstone Creek), a fault (delineated by the low-lying swampy area), Mesnard Quartzite, and Enchantment Lake Fmn.

Stop 2.6: Kitchi Schist agglomerate along Deer Lake Road (447197mE, 5151724mN [NAD83])

Follow Deer Lake Road north from the US-41 roundabout for a couple miles. Just before a small bridge, pull off to the right and view the pavement outcrop of Kitchi Schist (the oldest rock in the Marquette area). This agglomerate features a fine-grained ash matrix and numerous clasts of various lithologies and roundness.

Stop 2.7: Jasper "Knob" Hill - ***No rock hammers!*** (449753mE, 5148349mN [NAD83])

This famous, textbook outcrop of banded iron formation (BIF) features alternating, mm-cm-thick red silica (jasper), hematite, and magnetite bands. Small-scale structure (e.g., folding, faulting) is beautifully accentuated by the continuous layers. Note minor brecciation / conglomerates between beds.

This very upper portion of the Negaunee Iron Formation has undergone the initial stages of hydrothermal replacement of jasper by microplaty hematite. However, it is unclear whether siderite chert was oxidized and replaced by jasper (which was later replaced by hematite), or whether jasper and some banded hematite were primary.

Do not collect at this locality - excellent samples are available at the next stop. This point offers a nice view of the Cliff's Shaft in Ishpeming (to the northwest) and tailings piles of the Empire and Tilden open pit iron mines to the south. The highest waste pile (North Dump Area 5) is only 178 feet short of the highest point in Michigan – any higher, and it would require a light for navigation.

Stop 2.8: Little Mountain Mine (449742mE, 5148730mN [NAD83])

Use caution around the unmarked, water-filled pits and steep slopes.

This is just one of many "hidden", unmarked and generally unvisited historic iron mines in the Negaunee-Ishpeming area. It was the first mine on the range (opened 1849), and closed in 1855. In 2016, a 29-ton boulder (8' x 7' x 6-1/2') was hauled from here to be displayed at Michigan State University's Department of Earth and Environmental Sciences. Many excellent hand samples are available.

Stop 2.9: North Jackson Mine, along Iron Ore Heritage Trail (452177mE, 5149572mN [NAD83])

Located a short walk from the Iron Ore Heritage Trail is a water-filled pit and exploration adit of the North Jackson Iron Mine (opened in 1848). Signs describe this as the first open pit mine in the Lake Superior region. The south wall along the path is soft ore, while the north wall is a vertical-sheared chlorite dike. On the southeast side of the pit is a boulder pile of jaspillite that show hematite replacing jasper. Many blocks appear to be a breccia with cross-cutting hematite and magnetite veins. A short wooden boardwalk leads towards the exploration adit in the west wall, and a south pillar that shows vuggy metallic hematite with clay (kaolin?) filling. Initially hard hematite "jaspillite" was further leached by supergene processes with resulting dissolution of remaining jasper and formation of "classic" porous soft ore.

Day 3 – Tuesday, October 10, 2017: Tilden Mine, outcrops.

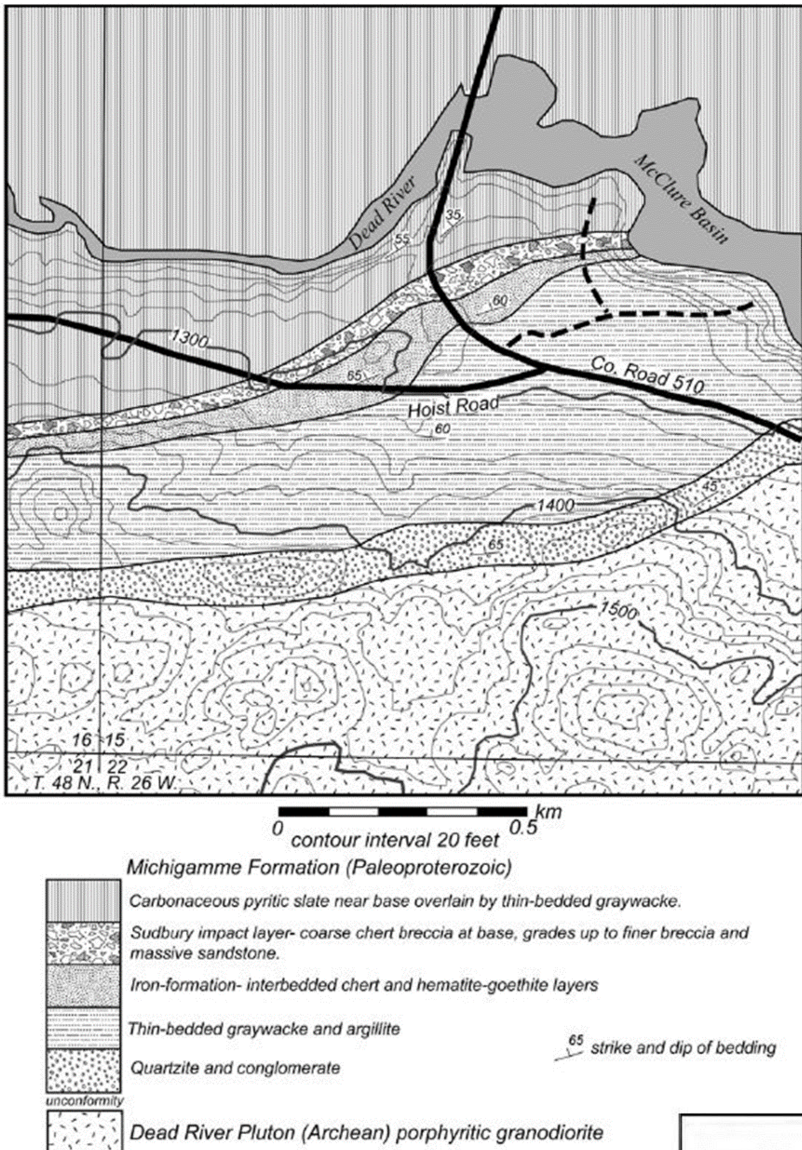
Stop 3.1: Dead River Bridge Impact Layer (458256mE, 5156125mN [NAD83])

(This stop description heavily references Field Trip 5: The Sudbury Impact Layer at the McClure Site by William F. Cannon, in Bornhorst & Klasner, 2008)

This set of outcrops along County Road 510 near an old abandoned bridge and a newly-built bridge display a complete section through the debris layer deposited from the 1850 Ma Sudbury impact event, located about 500 km to the east. Park at the little picnic area just south of the new bridge. The Sudbury layer here is breccia and sandstone (about 40 m thick), lying atop banded iron formation and overlain by pyritic black slate. Lithologies include: 1) the basal contact of the layer that consists of large rip-up clasts of the underlying iron-formation; 2) between here and Sudbury, ON, so this may be the most proximal ejecta layer in MI.

This site lies within the Dead River Basin, a structural outlier of the Paleoproterozoic strata located further south (towards Negaunee), surrounded by Neoarchean crystalline rocks. Here are various informal units of the Michigamme Formation. The impact-related layer was originally mapped as a chert conglomerate (Puffett, 1974). It sits atop a 60-m-thick unit of banded chert-hematite-goethite iron formation, which overlies an impure quartzite-argillite sequence that grades downwards into a basal quartzite-conglomerate that is likely equivalent to the Goodrich Quartzite along the Marquette Range. Immediately overlying the Sudbury layer is an apparent gradational contact with pyritic black slate.

Close examination of the layer will reveal an unusual mixture of volcanic fragments, chert clasts, and quartz sand grains. Thin section petrography revealed many shock metamorphic features: A small percentage of the quartz grains within the breccia matrix contain relict planar deformation features (pdf's) (i.e., lamellae of impact-generated glass resulting from breakdown of the crystalline structure) indicative of the 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. This is the best-exposed and thickest section of the Sudbury layer currently known in Michigan (no preserved 1850 Ma rocks occur in Michigan



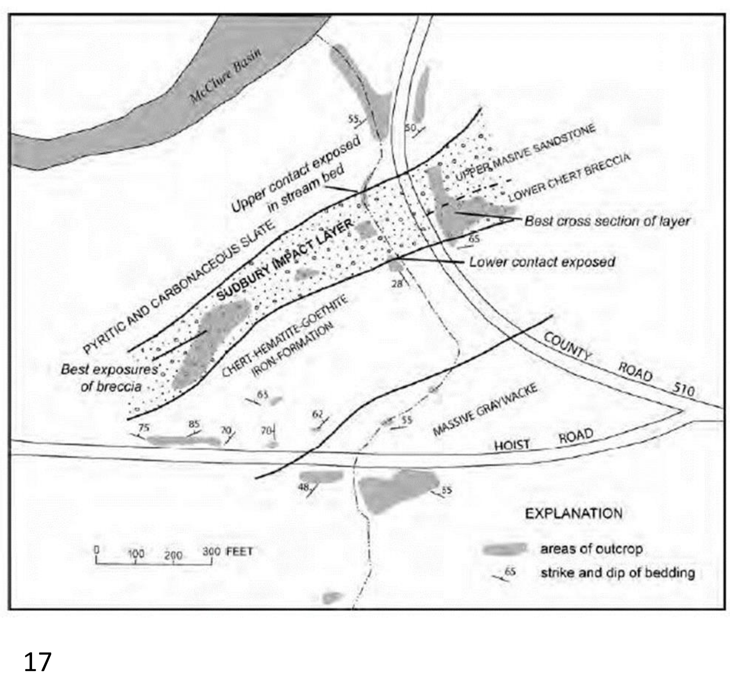


Figure 7: Geologic maps of the Dead River Bridge impact layer locality. Note: these maps show the old roadway; a new bridge has been built to the west. From Field Trip 5: The Sudbury Impact Layer at the McClure Site by William F. Cannon, in Bornhorst & Klasner, 2008.

extreme pressures generated instantaneously during a hypervelocity impact. The coarse chert breccia that comprises the unit's lower half grades upwards in size and abundance of locally-aligned clasts, set within a framework of clastic material and initially minor altered glass particles and accretionary lapilli that increase in abundance upwards. The unit above the breccia is a massive, dark grey-black impure sandstone with sparse angular chert pebbles and common glass particles; this may represent a post-impact turbidity flow.

Additional work is required to better understand this intriguing section.

Stop 3.2: Tilden Mine (453900mE, 5142917mN [NAD83])

Tour starts at 12:30 PM (2-3 hours long).

This mine visit is a good time to consider what factors turn simple mineralization into an economic venture… and what can mothball a project. Iron, the 4th most abundant element on earth, is not scarce, and neither are iron formations. Iron ore deposits require significant capital investment and 5-12 years to bring them into production.

(The following is from a presentation by R. Fink, October 13, 2010: Economic Geology of Iron Formations, Precambrian Research Center Workshop)

Direct shipping ore (DSO): >60% Fe; low capital and operating costs, simple crushing and screening; highest value, lowest risk. Product: lump and sinter fines.

Itabirities: >35% Fe; coarse grain size and best liberating characteristics; limited grinding required, upgrades cleanly (spirals, cyclones, column flotation. Product: sinter fines and concentrate, DRI-grade (direct reduced iron) pellet feed potential.

Lake Superior Type granular and banded iron formation (GIF and BIF): 25-35% Fe; fine grinding and pelletizing required; substantial CAPEX and OPEX; pellet feed market limited. Product: pellets.

Any GIF/BIF geologist must operate not only in the traditional mineral reserves realm (exploration, resource modeling, etc.), but also within mining and metallurgy (mining, beneficiation, pelletizing). Four elements are vital to quality iron ore reserve estimation: geology, tonnage factor or density, metallurgy, and mineable limits.

Day 4 – Wednesday, October 11, 2017: Eagle Mine. Marquette, MI to Houghton, MI.

Stop 4.1: Eagle Mine surface tour (432828mE, 5176975mN [NAD83])

Stop 4.2: Eagle Mine Exploration Office (457482mE, 5153196mN [NAD83])

Stop 4.3: Eagle Mine's Humboldt Mill (430950mE, 5148177mN [NAD83])

Stop 4.4: Champion Mine rock pile *(from Bornhorst & Klasner, 2008)* (424309mE, 5150880mN [NAD83])

Driving west on US-41, turn left up a hill at the blinking lights. The fenced-in mine area on the left is the Champion Mine; continue and turn left down road AT/AAJ for a short distance. The Champion Mine (operating on-and-off during 1867-1967) was accessed by seven shafts, some still visible. These tailings piles yield nice specimens of coarse specular hematite "specularite" and magnetite hard ore typical of iron mines in the western and southwestern parts of the range. Many alteration minerals are present. For details, see Banded Iron Formation of the Marquette District by T. Waggoner, in Bornhorst & Klasner (2008).

Part 2: Keweenaw Copper Country

Regional Geology

(The following is copied with minor modification from Bornhorst & Barron, 2011.)

The Midcontinent Rift (Fig. 8)

The bedrock geology of the western Upper Peninsula of Michigan is dominated by the 1.15–1.0 Ga Midcontinent Rift that extends more than 2000 km from Kansas through the Lake Superior Region and down to lower Michigan. Beneath Lake Superior, the rift is filled with more than 25 km of basalt-dominated volcanic rocks and 8 km of clastic sedimentary rocks, collectively termed the Keweenawan Supergroup.

About 5 km of rift-filling basalts are exposed in the Keweenaw Peninsula, dominantly the Portage Lake Volcanics. These voluminous basaltic lava flows were subaerially erupted from linear fissure vents in the center of the rift. Volatile degassing created sulfur-deficient basalts. A typical lava flow has a thickness of 10–20 m with a massive (vesicle-free) interior capped by a vesicular (locally termed amygdaloid) and/or brecciated (rubbly/broken; locally termed fragmental amygdaloid) flow top. The lateral extent of most flows is unknown; however, a few of the thicker flows have a strike length of up to 90 km. There are scattered interflow clastic sedimentary layers, up to 40 m thick, that constitute less than 5% by volume of the total the rift-filling volcanic section. These layers consist of red-colored pebble-to-boulder conglomerate, with lesser amounts of sandstone and occasional siltstone and shale. They are important for stratigraphic correlations within the pile of basalt lava flows. These clastic sediments were transported from the edges of the rift toward the center and deposited on the essentially flat-lying

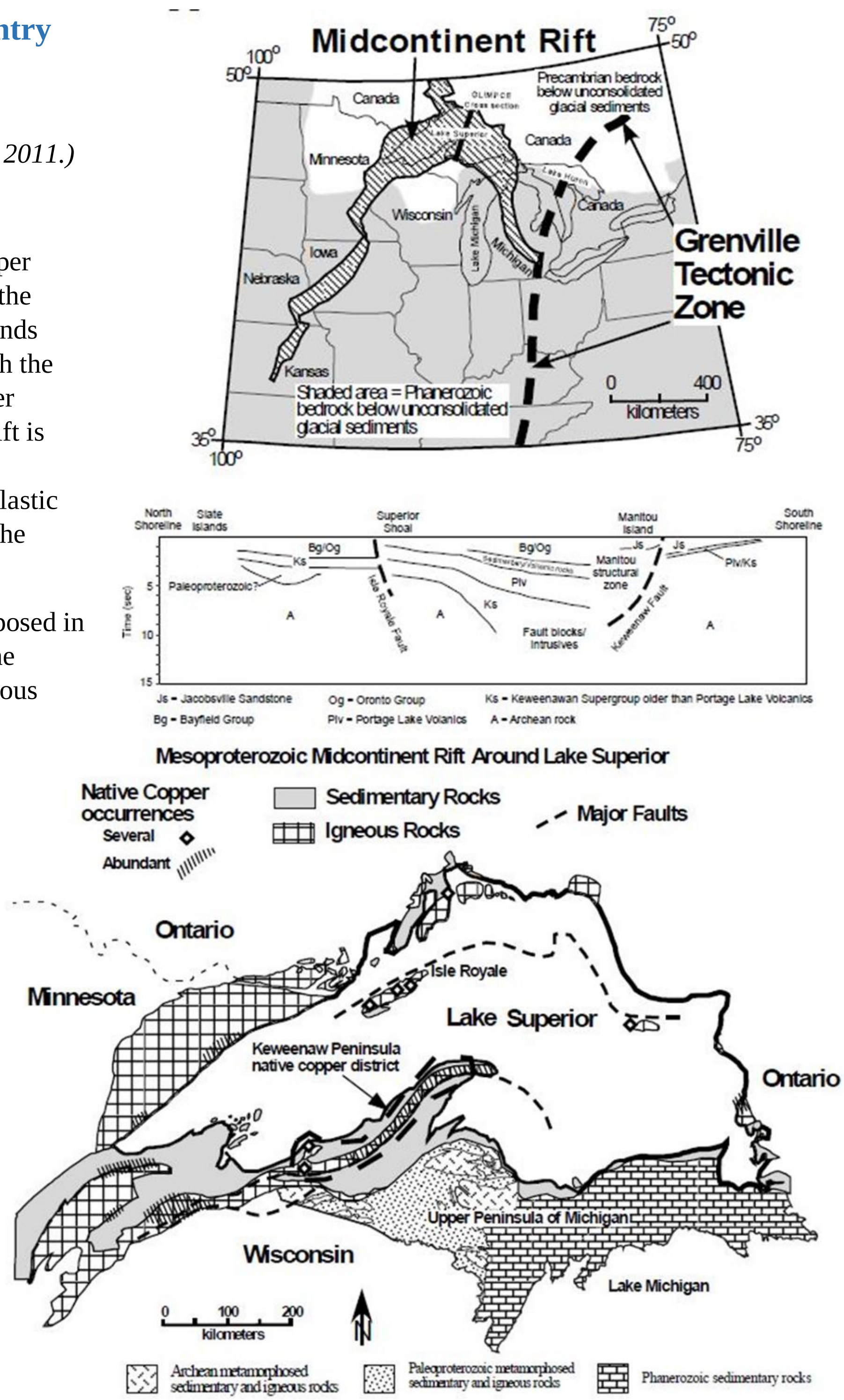


Figure 8: Regional maps of the Midcontinent Rift and associated strata. From Bornhorst & Barron (2013).

lava flows. As magmatic activity waned, the rift basin continued to sag. The resultant basin was filled with clastic sediments, the Oronto Group, with a maximum exposed thickness of ~6 km. The Copper Harbor Formation, the oldest rocks of the Oronto Group, are red-brown conglomerates and sandstones deposited in alluvial fans. Overall, this formation fines upward with the uppermost beds being dominated by red to red-brown sandstone. Within the lower part of the Copper Harbor Formation is a succession of interbedded subaerial lava flows, known as the Lake Shore Traps, representing some of the last significant magmatic activity in the Midcontinent Rift. (Fig. 9)

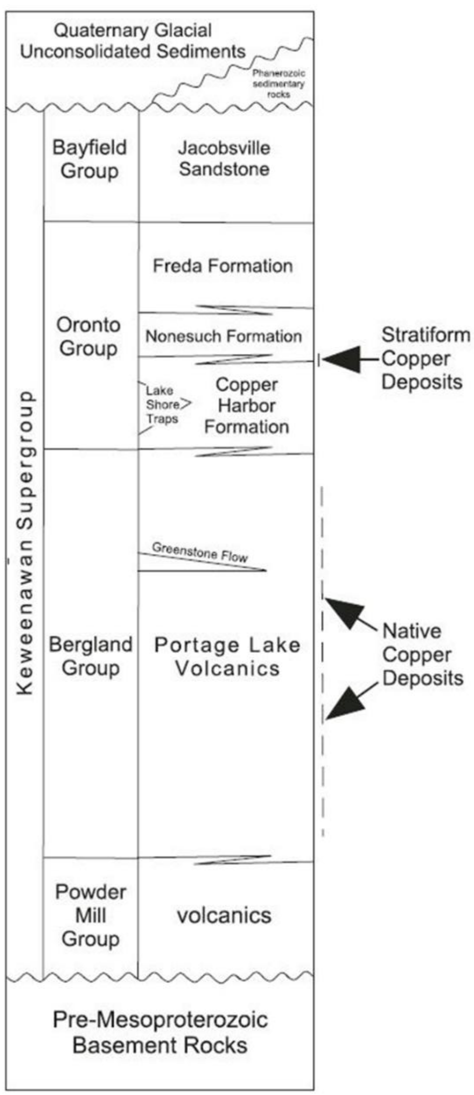


Figure 9: Lithostratigraphic geologic units of the Mesoproterozoic Midcontinent Rift System of Michigan. Native copper is known to occur in all of the Keweenawan Supergroup of Michigan except the Freda Sandstone.

The overlying Nonesuch Formation consists of gray-to-black siltstones, shales, carbonate laminates, and gray very fine-grained sandstone. The Nonesuch Formation was deposited in a lake with anoxic to oxic bottom conditions. The Freda Formation was the youngest rift-filling clastic sedimentary rock unit in Michigan; it consists of red-brown sandstone, siltstone, and mudstone deposited by shallow rivers. The last phase of the Midcontinent Rift was characterized by compression resulting from continental collision along the Grenville Front ca. 1.06 Ga. This collisional event transformed original graben-bound normal faults into reverse faults and created new fracturing, faulting, and minor folding of the rift-filling rocks. The Keweenaw fault is such a reversed graben-bounding normal fault that cuts off the base of the volcanic sequence along the length of the Keweenaw Peninsula. The Jacobsville Sandstone, over 3 km thick, was deposited by streams in a rift-flanking basin during and after active reverse movement along the Keweenaw fault (ca. 1.06–1.02? Ga).

Keweenaw Peninsula Native Copper District

The native copper district of the Keweenaw Peninsula represents the largest accumulation of native copper on the planet. Native copper accounted for nearly all of the metallic minerals in the mined ore bodies. The mines produced ~11 billion lbs of refined copper from 380 million tons of ore from 1845 to 1968. Small quantities of native silver (less than 0.01% of the recovered metals) accompanied the native copper. The major ore producing horizons were geographically restricted to a 45-km-long belt within the rift-filling volcanic rocks with a cluster of small mines to the southwest. Deposition of native copper in mineable quantities required a favorable combination of permeability and porosity for movements of copper-bearing hydrothermal fluids. Brecciated and amygdaloidal flow tops (58.5% of production), interflow conglomerate beds (39.5% of production), and cross vein systems (~2% of production) are the favorable sites that host economic native copper. Native copper occurs in vesicle fillings (up to a few cm across) and in open spaces between breccia clasts (small-to-moderately sized masses weighing up to several lbs and rarely

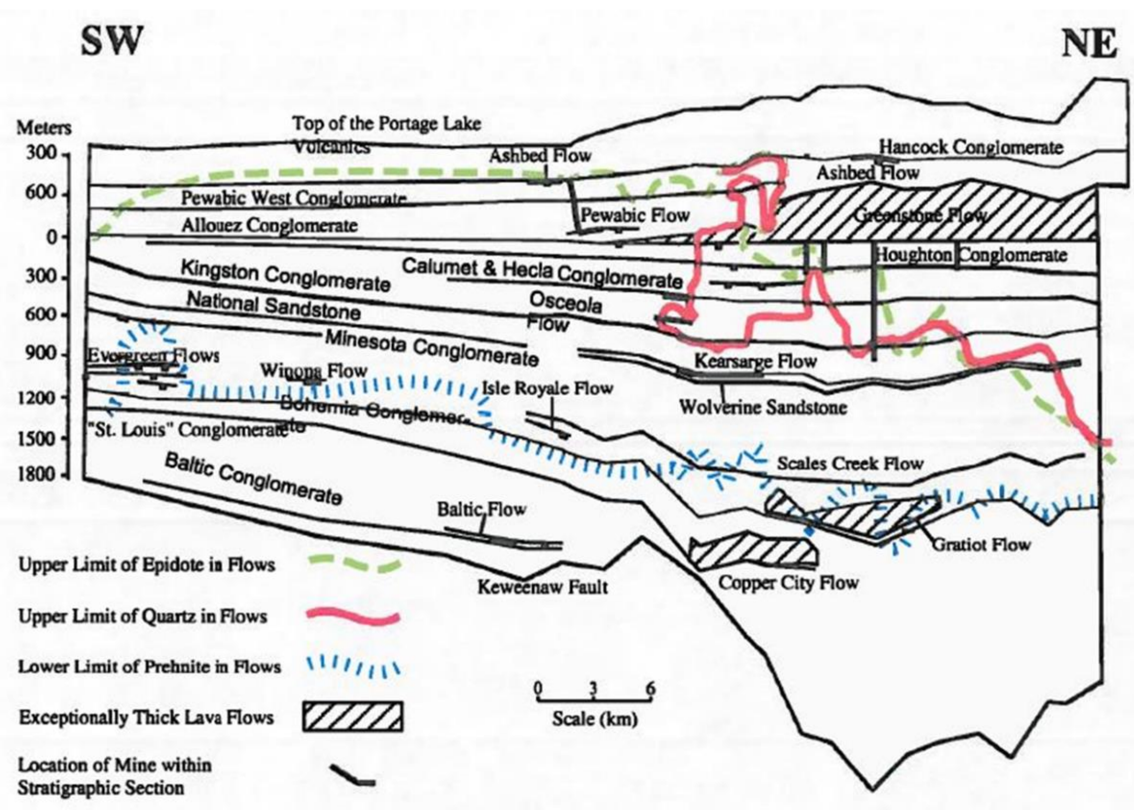
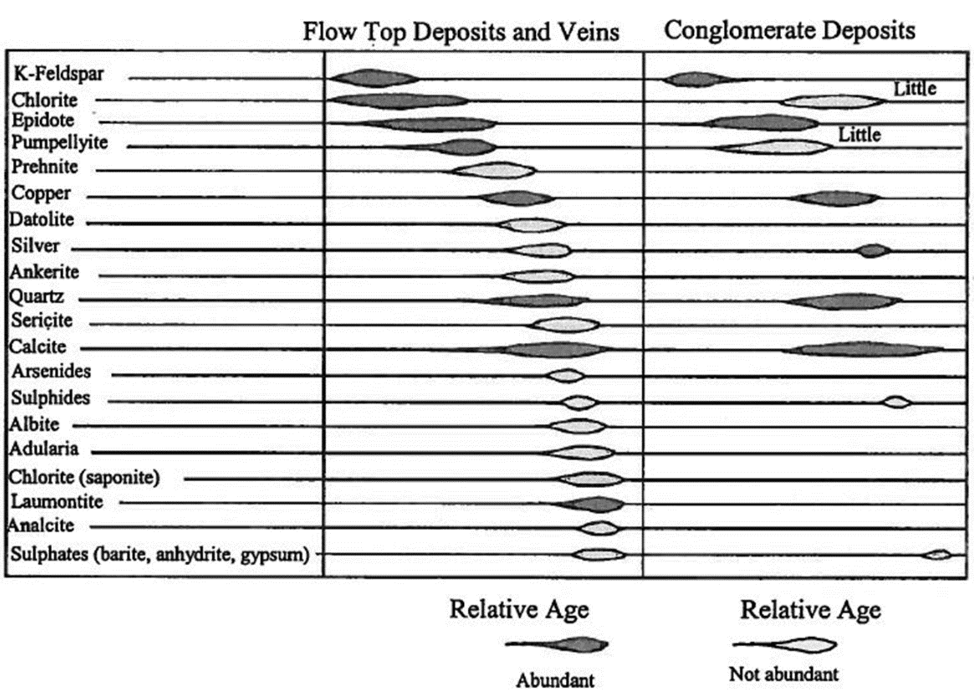


Figure 10 (above): Generalized section parallel to strike of the Portage Lake Volcanics from Victoria to Copper Harbor. Note the limits of three major amygdule- and vein-filling minerals.
Figure 11 (below): District-wide average paragenesis of secondary minerals in native Cu deposits.
Both figures from Phelps Dodge Exploration Annual Meeting and Workshop, 2005: Copper Deposits of Western Upper Peninsula by Theodore J. Bornhorst.



weighing tons). The most common host for native copper deposits was a brecciated flow top (a.k.a. fragmental amygdaloid) “sandwiched” between underlying barren massive basalt of the same flow and overlying barren massive basalt of the succeeding flow. These tabular lodes were typically 3 to 5 m thick, with a lateral (strike) extent of 1.5 to 11 km, and from 1.5 to 2.6 km down- dip. Interflow clastic sedimentary layers host a disproportionate amount of native copper. Interflow sediments make up less than 5% by volume of the volcanic section, but accounted for nearly 40% of the district’s production. These clastic sedimentary rock hosted deposits are “sandwiched” between overlying massive basalts and underlying lava flow tops. The largest single native copper lode in the district, the Calumet and Hecla (C&H) conglomerate, yielded 4.2 billion lbs of copper at a grade of 2.85% Cu over a strike length of 4.9 km and 2.8 km down-dip. The earliest mines in the Keweenaw native copper district, such as the Cliff Mine, exploited veins that cut beds at high angles but were of minor economic importance. Large masses of native copper were more common in veins than in lode deposits. These large masses, some weighing as much as 400 tons, created problems for miners as they had to be grooved by hand chiseling before blasting into more manageable chunks for hoisting to the surface.

There are over 100 different hydrothermal minerals, with a lesser number of widespread and locally important minerals, closely related in time and space with the native copper mineralization (Fig. 10-11). These hydrothermal minerals filled vesicles, voids in brecciated basalt and clastic sedimentary rocks, veins, and micro-to-macro porosity in otherwise massive rocks as replacements. The absolute age of hydrothermal activity is ca. 1.06 Ga. Native copper in Keweenawan basalts and interflow clastic sedimentary rocks occurs throughout the exposed Midcontinent Rift and implies a rift-wide mineralizing process. A copper-rich ore fluid can readily be generated by burial metamorphism of rift-filling basalts at temperatures of 300 °C to 500 °C. More than adequate amounts of copper are available for leaching from the basalts, and based on reasonable assumptions, leaching of copper from ca. 10 km of basalt beneath the present ore horizons is sufficient for all the known copper mineralization. The low sulfur content of rift-filling basalts, which were both source rocks and host rocks, facilitated native copper deposition, rather than copper sulfide. Buoyant ore fluids followed permeable pathways such as brecciated and vesicular lava flow tops, interflow sedimentary rocks, and fractures/faults. Compression produced a network of faults/ fractures that integrated the plumbing system and allowed for easier and more rapid upward movement of fluids that were focused into locally thick permeable strata. Native copper and related minerals were precipitated at ~225 °C by a combination of mechanisms including: mixing of ore fluids with cooler, oxidized, and more dilute resident fluids; ore fluid-rock reactions; and cooling of the ore fluids. The coincidence of compression with the generation of deep, burial metamorphic ore fluids may be the critical component in the genetic model that distinguishes this area from other flood basalt provinces that lack native copper deposits.

Copper sulfides are uncommon in the Keweenaw Peninsula native copper district although chalcocite occurs in veinlets cutting the native copper deposits. However, near the tip of the Keweenaw Peninsula, there are 12 small, unmined chalcocite-dominated deposits. The Gratiot deposit (543- S) is the largest of these containing ~4.5 million tons with an average grade of 2.9% Cu. These deposits occur near the Keweenaw fault in the lower most exposed stratigraphic units of the Portage Lake Volcanics. Copper sulfides at the Gratiot deposit are hosted by brecciated amygdaloidal flow tops and adjacent fractured flow interiors, as well as by two sill-like intermediate composition dikes. The highest copper grades occur near cross-cutting faults. The copper sulfide minerals appear to have been deposited after native copper. This paragenesis is the same for chalcocite in veinlets that cut native copper deposits. The genesis of these small chalcocite deposits is uncertain. It is likely that these deposits are on a mineralizing continuum with the native copper deposits, but perhaps had a very different fluid source, potentially influenced by basement rocks near the rift margin.

Mining History (Table 1)

When the Pleistocene glaciers retreated, very large volumes of water filled the Lake Superior basin with all but the very highest points in the Keweenaw Peninsula being submerged. As the glacial waters retreated, native people began exploiting native copper by ca. 7000 years ago. When European metals arrived around 1610, the native peoples no longer needed to mine Cu, but now the Europeans became interested in exploiting the native copper even though expeditions seeking copper were unsuccessful. Because of increased interest, H.R. Schoolcraft led a major expedition to northern Michigan in 1820. Schoolcraft led two more expeditions in 1831 and 1845, accompanied by geologist Douglass Houghton. Houghton became Michigan's first state geologist in 1840, and his 1841 report to Michigan's legislature started the first major mining rush in North America. From the beginning of historic mining in 1845–1890, profitable lodes of copper proved elusive. The first companies searched for mass copper in fissure veins and failed. Finally, in 1849, the Cliff Mine became the first profitable mine in the district. The Minnesota Mine became profitable soon after the Cliff. In the late 1850s and early 1860s, the Quincy Mine and several other mines in the Houghton area opened copper mines on flow top lodes instead of fissures. By the early 1870s, the Calumet and Hecla Mining Company opened a mine on the interflow Calumet and Hecla conglomerate.

The introduction of modern mining methods to the Keweenaw ca. 1880 accelerated the mining of copper. Hand drills were replaced by compressed air rock drills, high explosives replaced blasting powders, and steam engines to hoist and move ore replaced animal power. The processing mills that required large quantities of water were located alongside lakes. The tailings produced by ore crushing and extraction were simply dumped into the lakes in the absence of any environmental regulations. Fortunately, the tailings were not acid-generating, greatly limiting environmental damage to the district.

Table 1: Production from 1845-1968 of refined copper from Keweenaw native copper deposits.
From Bornhorst & Barron (2013).

Name of Deposit	Million lbs of Refined Cu Produced
Calumet & Hecla Conglomerate	4,229
Kearsarge Flow Top	2,263
Baltic Flow Top	1,845
Pewabic Flow Top	1,077
Osceola Flow Top	578
Isle Royale Flow Top	341
Atlantic Ashbed	143
Allouez Conglomerate	73
Houghton Conglomerate	38
Kingston Conglomerate	20
Greenland-Mass Subdistrict	72
Other Flow Top and Conglomerate Deposits	137
Cliff Fissure	38
Central Fissure	53
Other Fissure Deposits	123
District Total	11,030

Copper production from the native copper district accounted for 80% of the nation's copper production in 1880 but soon declined to 25% by 1900 and to 15% by 1920, despite increasing absolute annual production from 50 million lbs in 1880 to 150 million lbs in 1900 to the absolute peak of 267 million lbs in 1916. The collapse of the copper market after the end of World War I in 1920–1921 caused many mines to close. During the Great Depression, the few remaining companies ceased or limited operation. Even the great Quincy Mine closed all its shafts from 1931 until 1937 after near continuous mining since the 1850s. Native copper mining ended in 1968 and has yet to resume. In 1992, local efforts at economic revival based on tourism resulted in creation of the Keweenaw National Historical Park in recognition of the historical importance of native copper mining to the history of the United States.

Quincy Mine

(The following is copied with slight modification from Bornhorst & Barron, 2011.)

The Quincy Mining Company, incorporated in 1848, opened nine shafts on the Pewabic lode and operated until 1967. The mine was developed along a series of parallel relatively thin lava flow tops within the Portage Lake Volcanics to a vertical depth of 1675 m (comprising 85 levels). The ore bodies decrease in dip from 55° at the surface, to 35° at the bottom levels. By 1925, the mine had produced ~725 million lbs of copper and 71 million ounces) silver. Production to 1968 totaled 1078 million lbs of copper, ranking it the fourth largest mine in the native copper district. As compared to other basalt lava flows within the Portage Lake Volcanics, the Pewabic flows are distinguished by feldspar phenocrysts. Whereas the tops of most lava flows that host native copper deposits are brecciated, the Pewabic flows are characterized by cavernous zones or layers up to 1–1.5 m thick. Coalescing vesicles and large gas cavities formed these large connected openings. Connected openings in flow tops can extend for 3–30 m, and a series of such openings provided an almost continuous path for the flow of mineralizing hydrothermal solutions. Where coalescence is well developed, there may be 2 to 10 mineralized layers. Quartz and calcite are abundant cavity- and amygdule-filling secondary minerals; pumpellyite and epidote are less abundant. Chlorite is present in amygdules in the base of the flows, except near veins where it is replaced by quartz or calcite. Prehnite is present but not common, and laumontite is mostly confined to veins. Datolite was reported from upper levels of the mine, but not lower levels. Several prominent veins extend through the mine, dipping at high angles. These veins probably helped integrate the hydrothermal system as their mineralogy is similar to that of the secondary mineral assemblage in the flow tops.

Throughout its history, Quincy Mining Company paid dividends on such a regular basis it was nicknamed “Old Reliable.” At the time of closing, the number two shaft was over 9000 ft (2734 m) long on the incline and in 1921 was the world’s deepest shaft. Our tour will utilize a 700 m long adit that connects to the No. 5 shaft at the 7th level and old early excavations.

The No. 2 shaft of the Quincy Mine opened in 1858. At the beginning of mining, a simple house was built over the shaft. By 1892, Quincy introduced the concept of hoisting the ore and doing initial crushing and sorting of the ore in the same building, a shaft-rock house. The Quincy No. 2 shaft rock house was built in 1908 and replaced the previous shaft house, a gabled wooden structure, built in 1895. The Quincy No. 2 shaft rock house is 147 ft (45 m) tall and the angle on the side of the building facing US-41 is at the dip angle of the native copper lode. Behind the shaft rock house, there are two of the original eight pulley stands, stanchions that were used to support a steel cable extending to the No. 2 hoist house built in 1919. Mining at the No. 2 shaft ended in 1931. By 1917, the No. 2 shaft had reached a depth of almost 8000 ft (2440 m) on the incline, and the hoist engine housed in the 1895 hoist house was not adequate. This hoist was built by E.P. Allis Company in 1894 and at the time was the largest one they had ever built (but subsequently removed). The Quincy Mine needed a large and faster hoist to continue its record of production and 48 years of continuous payment of dividends. In 1918, the No. 2 hoist house was constructed, but World War I delayed delivery of a new hoist until 1919. The Nordberg hoist began operating in 1920 as the shaft reached an incline depth of 7750 ft (2360 m). The Nordberg hoist consists of four cross- compound steam engines that work as one. The new hoist could move an ore skip carrying 10 tons of rock (13 tons total weight) up at 3200 feet per minute (36 miles per hour) and was more energy efficient than the hoist it replaced. The Nordberg hoist operated for 11 years for 24 hours per day and, when mining ended in 1931, the shaft reached a depth of 9000 ft (2743 m) on the incline. The older 1895 hoist house now serves as the main entrance for the Quincy Mine Hoist Association operations, while the adjacent 1919, more modern, hoist house preserves the Nordberg hoist, the world’s largest steam hoist. In the back of the 1895 hoist house is a 17 ton boulder of native copper recovered from Great Sand Bay in

July 2001. Discovered in 1991 by local divers in 30 feet of water, this specimen represents the immensity of the native copper vein deposits which typically crosscut many of the lava flows along the Keweenaw Peninsula.

Our tour through the Quincy Mine Adit will show two main aspects of the Keweenaw Peninsula native copper district: 1) a long, high open stope follows a major horizon of mineralized flow tops (Pewabic) in an inclined sequence of basaltic flows; and 2) the oblique Hancock Fault offsets the basalts and forms the southeastern limit for the Pewabic orebody. A segment of this fault was mineralized and mined at the Hancock Mine; it may have been a feeder through which mineralizing solution reached the Pewabic flow tops. We will walk across 12 lava flows below the Allouez Conglomerate. At the top of the Allouez Conglomerate is a clay gouge associated with a bedding plane fault (a common feature in this district). The Hancock Fault is marked by a distinctive clay gouge and a green, brecciated alteration zone adjacent.

Day 5 – Thursday, October 12, 2017: Quincy Mine, A.E. Seaman Mineralogical Museum, outcrops.

<u>Stop 5.1: Quincy Mine (part of the Keweenaw Heritage Site of the Keweenaw National Historical Park) (380658mE, 5221444mN [NAD83])</u>

Tour starts at 9:00 AM.

<u>Stop 5.2: A.E. Seaman Mineralogical Museum *(Copied directly from Bornhorst & Barron, 2011.)*(382221mE, 5218635mN [NAD83])</u>

A.E. Seaman Mineral Museum is one of North America's great mineral museums. The A.E. Seaman Mineral Museum is the official mineral museum of the State of Michigan. The museum features the world's best collection of crystallized native copper and native copper in calcite, including arguably the finest crystallized native copper specimen from a now dormant Keweenaw native copper district. The museum's display of fluorescent minerals is among the best of any mineral museum. While the museum is noted for its Lake Superior region collections, it also has outstanding suites of minerals from around the world.

<u>Stop 5.3: Float Copper at Keweenaw National Historic Park *(Description partly from Bornhorst & Barron, 2013.)* (390409mE, 5233107mN [NAD83])</u>

A float copper boulder weighting 4,263 kg (9,392 lbs) is on display here. This mass of glacially transported native copper was found in 1970 about 4.5 miles SW of Calumet in less than three feet of surficial sediments. Native copper deposits of the Keweenaw Peninsula were exposed at the bedrock surface at the time of the last period of Pleistocene glaciations. The glacial ice plucked masses of malleable native copper from the tabular lodes and fissures which were subsequently smoothed and flattened by abrasion from other rocks carried by the glacial ice. When the glaciers retreated about 10,000 years ago, unconsolidated rock debris (rounded boulders to clay sized material) were left behind by the melting ice including masses of native copper such as this one "floating" among the unconsolidated rock debris. While some of the rocks in the glacial deposits are from far north of the Keweenaw Peninsula, most of them are recognizable as from local MCR strata exposed in the Keweenaw Peninsula. The large float copper masses could not have moved far from their source, but smaller masses have been transported quite far and have been found in Lower Michigan and Wisconsin. The largest known float copper was discovered in the early 2000s and weighed about 25 tons (50,000 lbs) near the Houghton County airport; it was cut into smaller masses and sold to be smelted and refined. Most pieces of float copper are small, ranging from a few to 50 cm across. The famous example of float copper was the Ontonagon boulder, a 3,700 pound specimen visited by numerous explorers and finally removed from the Keweenaw to the nation's capital in 1843. The Ontonagon boulder is part of the Smithsonian's collection.

This and other float copper masses have been surface altered by oxygenated groundwater and shallow precipitation since the glaciers retreated.

This surface alteration consists of forms of copper including cuprite (copper oxide; Cu_2O), tenorite (copper oxide; CuO), malachite (hydrated copper carbonate; ($Cu_2(CO_3)(OH)_2$) and rarely azurite (hydrated copper carbonate, ($Cu_3(CO_3)_2(OH)_2$). Even when small cm sized masses of float copper are cut, the typical surface alteration is less than one mm thick; native copper is highly resistant to surface weathering. Float copper makes an attractive decorator specimen when a part of the surface is polished and buffed exposing shiny copper color.

The basalt mine rock buildings are part of the Keweenaw National Historical Park. The park was established on October 27, 1992, by U. S. Congress Public Law 102-543. The enabling legislation ascertained that the Keweenaw was nationally significant because of: its unique geology; the prehistoric use of its copper by Native Americans; the importance of the region as a leading copper producer and developer of new technologies; its long history of corporate paternalism; and because it became home to so many European ethnic groups that migrated to the United States. Older mining districts typically had only single-industry economies and when the mines shut down, the communities suffered major contraction. In 1910, nearly 40,000 people resided within a few miles of here whereas now, fewer people live in all of Houghton County.

The idea that maybe the future of Calumet resided in its past was generated in the late 1980s; history could be "sold" to revitalize the community by increasing tourism. The national park itself only owns a few structures in Calumet, including these, and instead relies on public and private partners termed Keweenaw Heritage Sites. The heritage sites contain and interpret significant cultural and/or natural resources that together with park assets help tell the story of copper mining in the Keweenaw Peninsula. The Quincy Mine property on the edge of Hancock and the A.E. Seaman Mineral Museum on the campus of Michigan Tech are two among multiple Keweenaw Heritage Sites.

Day 6 – Friday, October 13, 2017: Houghton, MI to Copper Harbor, MI. Outcrops and mineral collecting.

Stop 6.1: Razorback Center *(Description from Bornhorst & Barron, 2013.)* (379772mE, 5218757mN [NAD83])

The rock cut at the edge of the parking lot in the rear (south side) of Razorback Center, Houghton provides an excellent example of the characteristics of subaerial basalt lava flows that comprise the Portage Lake Volcanics, the host rock unit for native copper deposits of the Keweenaw Peninsula native copper district and the rock unit that holds up the spine of the Keweenaw Peninsula. This exposure of subaerial lava flows is located stratigraphically between the Calumet and Hecla and Kingston Conglomerates. It is also located between the stratigraphic level of the Isle Royale and the Quincy Mines. The lava flows strike about N30˚E and dip about 55˚ to the northwest (towards Lake Superior). The rock cut is at an oblique angle to the strike of the lava flows. When facing the exposure, the stratigraphic top is towards the northwest or toward the right. At the far eastern end, or far left, only the amygdaloidal top of the oldest basalt lava flow in this rock cut is exposed. Stratigraphically upwards, towards the west/right, this flow top is overlain by a thick section of dark-gray to black massive basalt representing the interior of a prominent lava flow. Progressively, the abundance of amygdules increases upwards and the color of the basalt changes to greenish tones reflecting an increased degree of alteration. This zone represents the amygdaloidal top of the prominent lava flow in this rock cut. The amygdules tend to be concentrated along layers and near the upper contact; they coalesce into a continuous now filled open space. The contact between the amygdaloidal top of this prominent lava flow and the massive basalt of the overlying flow is well exposed. Along most of the exposed contact, amygdaloidal basalt lies directly below the massive basalt indicating the lava flow had a smooth top (pahoehoe lava flow), however, at the level of the parking lot, the planar contact bends and there is a small zone of brecciated flow top. The entire cross section of the prominent lava flow is exposed in the Razorback Center rock cut. A typical lava flow in the Portage Lake Volcanics is between 10 to 20 m thick, the prominent lava flow at Razorback Center. Stratigraphically further upwards, towards the west, the prominent lava flow is overlain by a thick section of dark-gray to black massive basalt representing the interior of the overlying flow. On the far western end, there is amygdaloidal basalt representing the top of this overlying flow; an almost complete cross section of this flow is exposed here.

Volcanic textures and structures at Razorback Center are typical of subaerial lava flows within the Portage Lake Volcanics. The basalts are mainly olivine tholeiites erupted as thick, ponded subaerial lava sheets. The very top and bottom of such lava flows typically consist of aphanitic chilled basalt. The contact between the underlying and overlying lava flows occurs where amygdules disappear abruptly and the overlying flow consists of massive basalt. The upper surface of the main flow was brecciated slightly by movement of lava after the formation of an upper crust, but rapidly grades downward to a non-brecciated, highly vesicular flow top. The layered nature of amygdules in the prominent flow here at Razorback Center is likely a result of preferential accumulation of vesicles along laminar flow planes. The flow top breccia is laterally discontinuous for this flow. Slow cooling of the lava flow caused solidification toward the flow interior at a rate which allowed development of subophitic to ophitic textures (large oikocrysts of clinopyroxene enclosing a felted framework of An-rich plagioclase and intergranular olivine). The resulting massive, non-vesicular flow interior constitutes about two-thirds of the flow. The effects of regional hydrothermal alteration can be observed within the amygdaloidal flow tops. The massive interiors are much less altered except along fractures. The original plagioclase in the massive basalt has been replaced by albite and the mafic minerals by chlorite, pumpellyite, and iron oxides. The massive interior of the flow is much less altered than the flow top which represents a relatively impermeable horizon in the paleohydrologic system except in the vicinity of selected fractures. The pseudomorphic alteration minerals in the massive interior of the basalt are similar to those which fill the amygdules. The amygdules here are filled with a variety of secondary minerals including: calcite, chlorite, epidote, prehnite, pumpellyite, quartz (not in order of abundance), and traces of native copper. Late stage laumontite abundantly fills some amygdules.

Stop 6.2: Cliff Mine rock pile *(Description from Bornhorst & Barron, 2013.)* (400850mE, 5247383mN [NAD83])

Fissure (vein) deposits were of little importance to the overall copper production from the Keweenaw Peninsula native copper district. Only a few fissure mines, including the Cliff Mine, were profitable. The Cliff Mine worked the Cliff fissure (vein) from 1845 to 1887 and produced a total of about 38 million lbs of refined copper. The Cliff fissure is nearly at right angles to the attitude of bedding and dips steeply to the east. The productive portion of the fissure is under the Greenstone flow. While most of the mineralization was confined to the fissure, some lava flow tops (amygdaloids) cut by the fissure contained native copper. Multiple large masses of native copper, some up to 100 tons, were taken out of the Cliff Mine. Among the fissure deposits, the Cliff Mine produced the most native silver. Minerals other than native copper and native silver include adularia, apophyllite, calcite, chlorastrolite, chlorite, datolite, epidote, laumontite, and prehnite (alphabetical). Many specimens contain multiple minerals and illustrate paragenetic relationships.

Fissures ranges in size from tight cracks to more than 3 m wide. In this part of the native copper district, fissures strike across the lava flows and dip steeply. Fissures formed as tension cracks related to bending of the lava beds, transverse to the axis of the MCR. The steep ridge near the Cliff rock pile is the Greenstone flow. Here it makes up the entire high ridge from bottom to top and with a northward dip of about 25°. The very thick massive relatively impermeable interior of the Greenstone flow likely played an important role in the localization of native copper. The fissures acted as efficient pathways for fluid movement. On a local scale, fluids migrating upward through these open fractures and were impeded beneath the massive interior of the Greenstone flow and were forced to move laterally into adjacent permeable horizons. In general, flows beneath the thicker section of the Greenstone flow in this area contain more dispersed native copper than elsewhere, but economic deposits are not common.

Stop 6.3: Central Mine rock pile *(Description from Bornhorst & Rose, 1994.)* (409617mE, 5251259mN [NAD83])

The Central Mine worked a fissure vein striking nearly at right angles to bedding and dipping steeply to the east. The mine operated from 1854 to 1898 and produced about 52 million lbs of copper. The fissure extends from just below the Greenstone Flow to the Kearsarge Conglomerate. A strike fault at the Kearsarge Conglomerate offsets the vein to the west, and below this it is not mineralized.

The town of Central was settled in 1854 mainly by Cornish immigrants. Later immigrant groups to the copper mining towns included: Italian, German, Croatian, and Finnish people.

Stop 6.4: Eagle River Falls *(Description from Bornhorst & Barron, 2013.)* (402200mE, 5251810mN [NAD83])

The water falls of Eagle River is near the contact between the top of the Portage Lake Volcanics and the base of the Copper Harbor Formation. The contact dips about 30˚ NNW. The beds strike roughly parallel to the shoreline of Lake Superior; the orientation of the Keweenaw Peninsula changes from NE in vicinity of Houghton to ENE at Eagle River to E-W near the tip. The tholeiitic basalt subaerial lava flows just below the contact are pahoehoe with ropy upper surface. The orientation of the ropes indicates that the flow was erupted from a vent to the north geographically under Lake Superior. That the ropy flow top is preserved suggests that little erosion occurred between deposition of the last of the lava flows of the Portage Lake Volcanics and the Copper Harbor Formation. The Copper Harbor Formation consists of red-brown rhyolite-pebble conglomerate, but includes many sandstone and even some shale beds. Under the bridge, one can get a good view of the lithology of the lower part of the Copper Harbor Formation. The Copper Harbor Formation was deposited in an alluvial fan shed off of a highland area to the SE (opposite of Lake Superior) likely buried under the rift-flanking Jacobsville Sandstone.

This contact marks an abrupt change in the geologic evolution of the Midcontinent rift. Below this contact there is a thick succession of basalt subaerial lava flows with more than 200 individual flows and a cumulative thickness of about 5,000 m, thus magmatic activity dominated the Midcontinent rift at that time. Abruptly above the contact lava flows are strikingly absent and clastic sedimentation dominated the Midcontinent rift.

Stop 6.5: Hunter’s Point Park (Fig. 11) *(Description from Bornhorst & Barron, 2013.)* (432226mE, 5258249mN [NAD83])

The Copper Harbor Formation is composed of volcanogenic clastic sedimentary rocks, dominantly conglomerates with lesser sandstone, siltstone, and shale. These rocks were deposited in a fining upward prograding alluvial fan complex. Typically conglomerates are composed of clasts with a ratio of mafic-to-intermediate+felsic composition of about 2:1. Towards the tip of the Keweenaw Peninsula, the Copper Harbor Formation is informally subdivided into an inner (land side) “member” and an outer (lake side) “member.” Between these two “members” there is a thin succession of interbedded lava flows collectively known as the Lake Shore Traps. The Lake Shore Traps consist of Fe-rich olivine tholeiite, basaltic andesite, and andesite lava that were erupted during the waning stage of volcanism within the MCR; the youngest flows tend to be more intermediate in composition. At 1087.2 +/- 1.6 Ma, the Lake Shore Traps are among the youngest magmatism within the MCR. The thickest section of the Lake Shore Traps is about 15 km to the east at the tip of the peninsula. Volcanologically, the lower lava flows are interpreted as erupted as ponded sheets while the upper lava flows erupted on a low positive slope such as a shield volcano. The Lake Shore Traps were subaerially erupted pahoehoe lava flows.

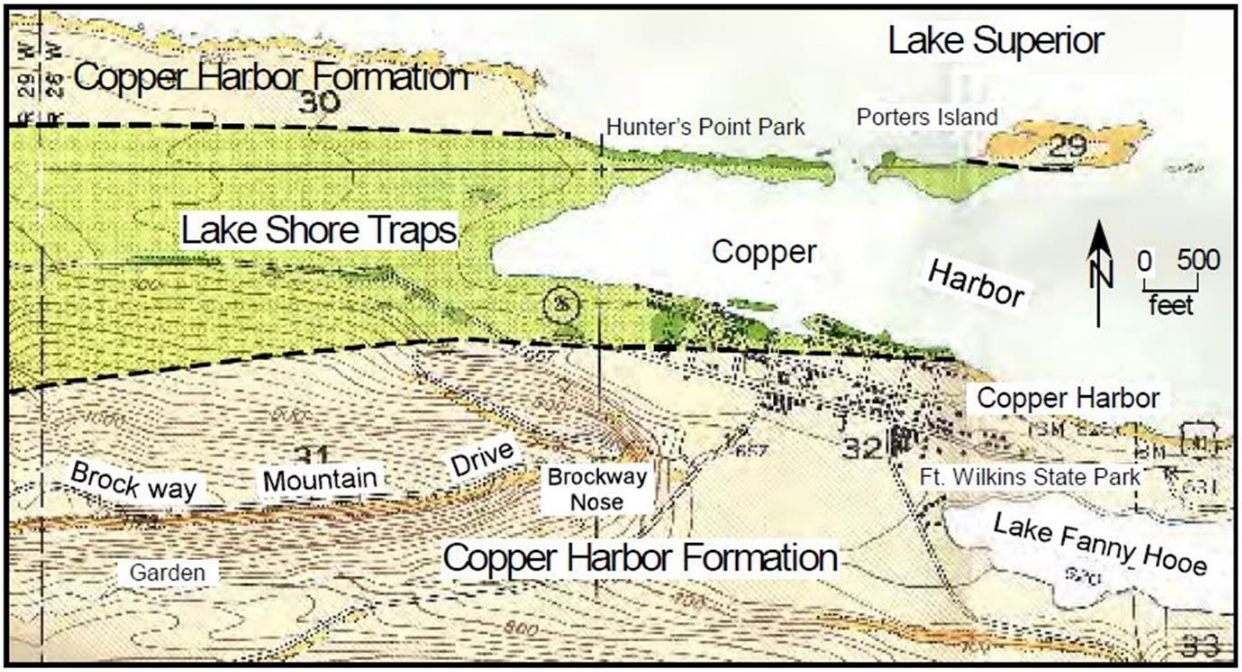


Figure 11: Geologic map of the Copper Harbor area. From Bornhorst & Barron, 2013.

At Hunter's Point, the top of the andesitic lava flows of Lake Shore Traps are conformably overlain by contact conglomerates of the Copper Harbor Formation. The strike of bedding is about E-W and dip is about 35˚ to the north (towards the lake). The orientation of the contact is roughly parallel to the orientation of Hunter's Point. As the walkway ends, you will be on outcrops of lava flows of the Lake Shore Traps. Walking to the east, the beach gives way to a rocky shoreline. In erosional coves, you can see contacts between lava flows, represented by vesicular to amygdaloidal andesitic lava (top of the lava flow) overlain by massive andesitic lava (massive interior of the overlying lava flow). The massive lava flow interiors within the Lake Shore Traps often retain relict olivine and interstitial glass due to the overall low degree of alteration (weathering and hydrothermal). Highly visible red hematitic bands form circular patterns within the massive interior; this banding is interpreted to be the result of alteration. Secondary minerals filling amygdules include agate, chalcedony, quartz, laumontite, analcite, calcite, and smectite in amygdules; this suite of minerals is equivalent to zeolite facies metamorphism. In contrast, in massive lava flow interiors within the Portage Lake Volcanics the olivine and interstitial glass are completely replaced by Mg-Fe phyllosilicates and amygdule filling minerals are equivalent to higher degree of metamorphism (greenschist facies). The Lake Shore Traps are geographically more distal to the thermal high and increased hydrothermal activity that resulted in the native copper deposits, hence, lower degree and grade of burial metamorphic/hydrothermal alteration.

To the west from the walkway, you can see a rocky point extending towards Lake Superior. The rocks in this point are conglomerates of the Copper Harbor Formation. The sharp contact between the uppermost lava flow of the Lake Shore Traps and the conglomerates can be viewed on the eastern edge of this rocky point. The conglomerate above the contact is dominated by rounded to sub-rounded boulders that are matrix-supported. There are proportionately more basaltic and andesitic clasts in this conglomerate bed than stratigraphically higher elsewhere along the Lake Superior shoreline as these clasts are derived from erosion of the Lake Shore Traps updip towards the highlands on the edge of the rift (the updip rocks are now missing having been removed by erosion). The very poor sorting and fine matrix supporting the clasts suggest this conglomerate could have been deposited as a debris flow. Sedimentary debris flows are common in alluvial fan depositional environments. The Copper Harbor Formation was deposited in an alluvial fan derived from highlands to the south in the vicinity of Keweenaw Bay.

Additional outcrops of the Copper Harbor Formation can be seen on the far western end of the cobble beach. These outcrops consist of interbedded conglomerates and sandstone that are typical of the formation as a whole. There are several prominent white colored calcite -filled fractures (calcite veins) within these outcrops. The calcite veins are northerly oriented consistent with the orientation of faults cutting the Portage Lake Volcanics about 5 km to the south. Calcite veins are a common occurrence in the Copper Harbor Formation and some of them contain native copper.

Stop 6.6: Estivant Pines Nature Sanctuary (433820mE, 5255110mN [NAD83])

Estivant Pines encompases 510 acres of one of the last old-growth white pine stands in Michigan. The story behind it – relating to Michigan's timber industry – is intimately woven along with mining into Michigan's history. Two trail loops lead through the towering pines; the one-mile Cathedral Grove loop (passes some of the oldest and largest giant white pines, over 125 feet tall and 500 years old). The 1.2-mile Bertha Daubendiek trail passes pines, maples, and oak. Together, the trails comprise a 2.5-mile-long hike.

Stop 6.7: Brockway Mountain Viewpoints (426968mE, 5257203mN [NAD83])

Brockway Mountain is a conglomerate ridge that reaches and elevation of over 400 m, with excellent views of the ridge and valley topography of the northern shore of the Keweenaw Peninsula. We will stop at two lookouts: one overlooking Copper Harbor and Lake Fanny Hooe to the east, and another at the peak with unobstructed viewing in every direction.

Day 7 – Saturday, October 14, 2017: Copper Harbor, MI to Sudbury, ON. Rock shop en route.

Stop 7.1: Prospector's Paradise rock shop (393256mE, 5237442mN [NAD83])

This shop hosts a great assortment of Keweenaw minerals, as well as curiosities from around the world, and will allow participants an opportunity to fill any missing spots on their "want lists".

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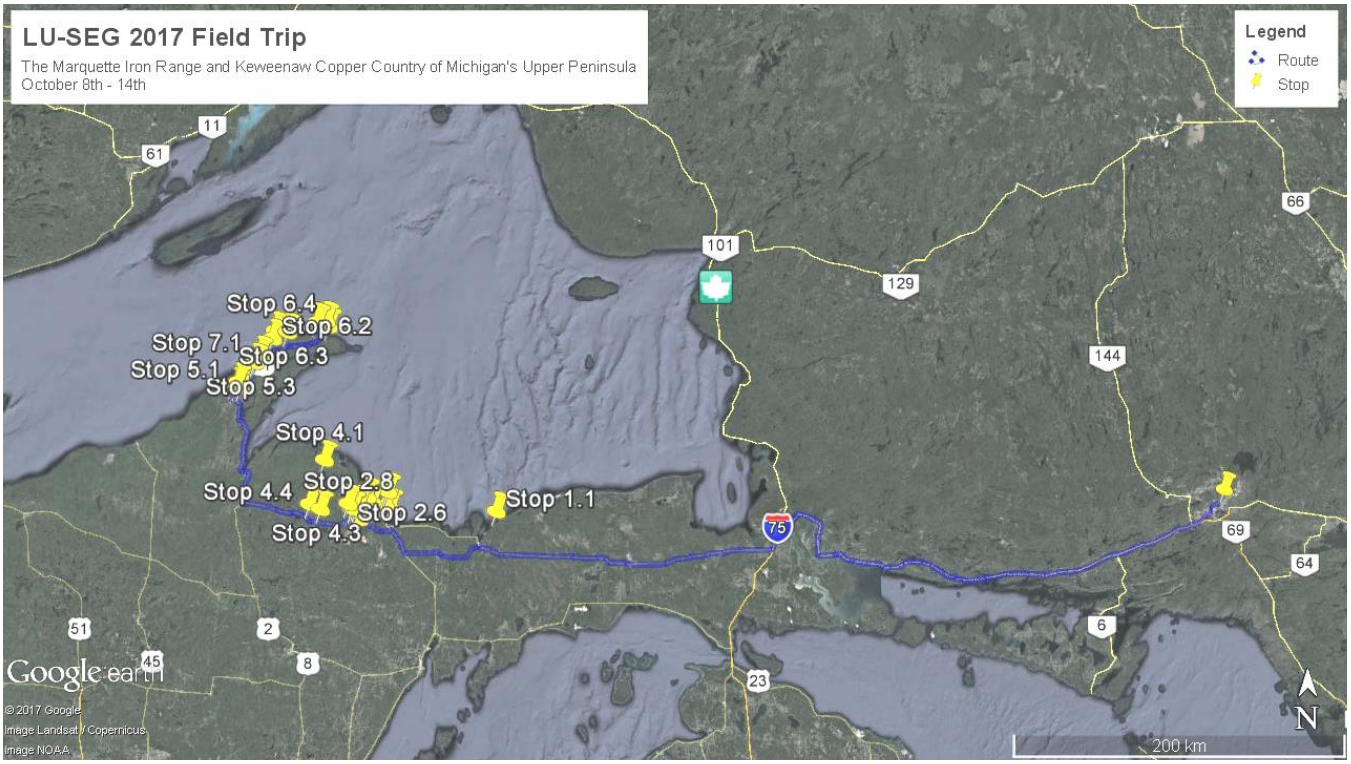
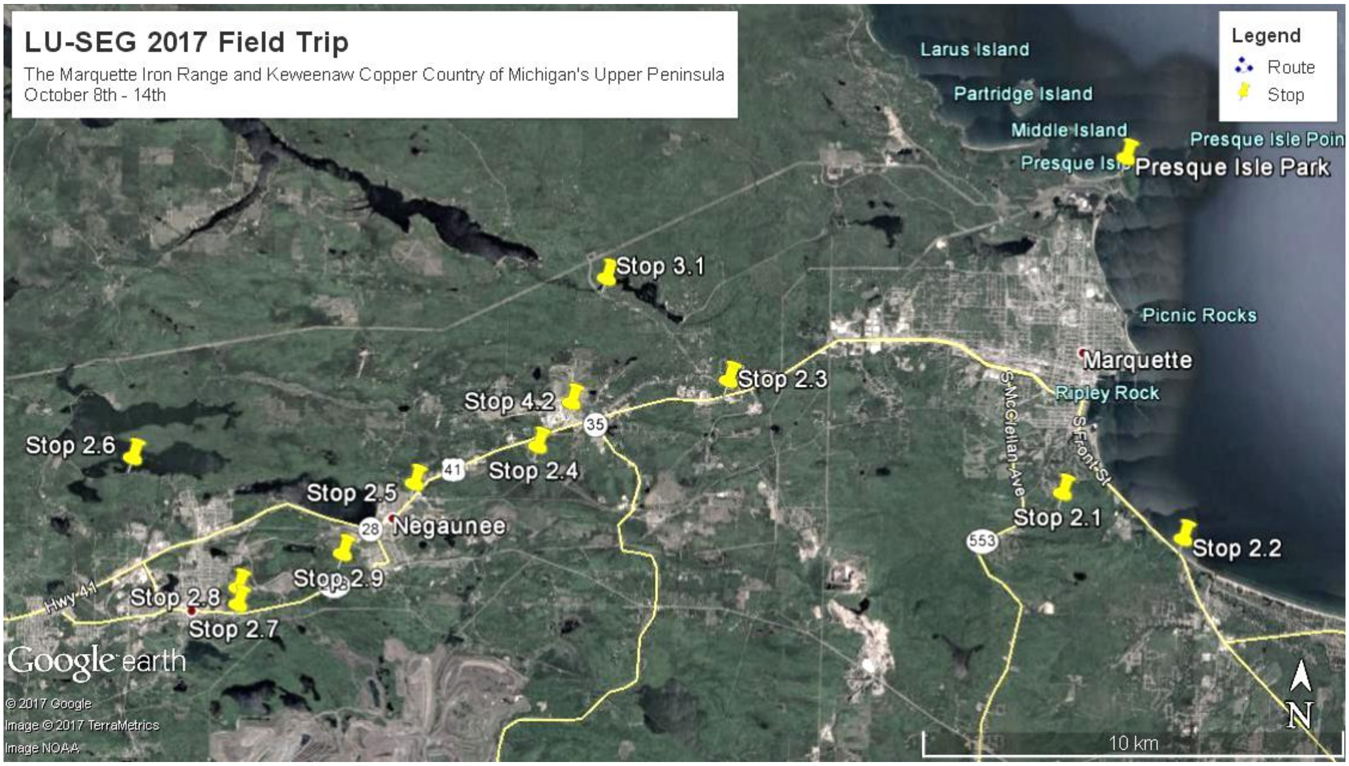
Appendix A: Route Maps




LU-SEG 2017 Field Trip
The Marquette Iron Range and Keweenaw Copper Country of Michigan's Upper Peninsula
October 8th - 14th
Legend
Route
Stop
Larus Island
Partridge Island
Middle Island
Presque Isle Point
Presque Isle Park
Stop 3.1
Picnic Rocks
Marquette
Ripley Rock
Stop 2.3
Stop 4.2
Stop 2.6
Stop 2.4
Stop 2.5
Negaunee
Stop 2.1
Stop 2.2
Stop 2.9
Stop 2.8
Stop 2.7
Hwy 41
S McClellan Ave
S Front St
10 km
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LU-SEG 2017 Field Trip
The Marquette Iron Range and Keweenaw Copper Country of Michigan's Upper Peninsula
October 8th - 14th
Stop 6.5
Stop 6.7
Stop 6.6
Stop 6.4
Stop 6.3
Stop 6.2
Stop 7.1
Stop 5.3
Stop 5.1
Houghton
Stop 5.2
Stop 6.1
Legend
Route
Stop
20 km
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