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# *Copper deposits of the western Upper Peninsula of Michigan*

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## ABSTRACT

**The western Upper Peninsula of Michigan is well known for hosting significant concentrations of copper in copper-dominated deposits. Most of the copper is hosted by rocks of the Mesoproterozoic Midcontinent Rift. Copper deposits in the western Upper Peninsula can be subdivided into two overlapping world-class copper mining districts. The Keweenaw Peninsula native copper district produced 11 billion lbs of copper and a lesser unknown but significant quantity of silver. Native copper deposits in this district are stratiform and hosted by tops of rift-filling subaerial basaltic lava flows and interflow coarse clastic sedimentary rocks. These deposits are interpreted to be the result of mineralizing hydrothermal fluids derived from rift-filling basaltic volcanic rocks that migrated upwards, driven by late Grenvillian compression of the rift some 40–50 million years following cessation of active rifting. The Porcupine Mountains sediment-hosted copper district produced or potentially will produce 5.5 billion lbs of copper and 54 million ounces of silver. These stratiform/stratabound deposits are hosted in rift-related black to gray shale and siltstone and dominated by chalcocite rather than native copper. Chalcocite is interpreted to be the result of introduction of copper-bearing fluids during diagenesis and lithification of host sediments. At the now-closed White Pine Mine, the chalcocite mineralizing event was followed by a second stage of native copper deposition that demonstrates a spatial and temporal overlap of these two world-class mining districts. While these two districts have been dormant since 1996, favorable results from recent exploration at Copperwood suggest a revival of the mining of copper-dominated deposits in the western Upper Peninsula of Michigan.**

Bornhorst, T.J., and Barron, R.J., 2011, Copper deposits of the western Upper Peninsula of Michigan, *in* Miller, J.D., Hudak, G.J., Wittkop, C., and McLaughlin, P.I., eds., [[space for volume title space for volume title space for volume title space for volume title]]: Geological Society of America Field Guide 24, p. 83–99, doi:10.1130/2011.0024(05). 

## INTRODUCTION

The western Upper Peninsula of Michigan hosts a variety of metallic mineral deposits that have been, are, or have potential to be mined. These deposit types include banded iron, magmatic nickel–copper±platinum group elements sulfide, gold, volcanogenic massive sulfide and stratiform/stratabound copper. Copper-dominated deposits of the western Upper Peninsula of Michigan represent a major geologic resource (Fig. 1 and Table 1). Economic concentrations of copper are hosted by Mesoproterozoic rocks associated with the Midcontinent Rift. The Keweenaw Peninsula native copper and Porcupine Mountains sediment-hosted

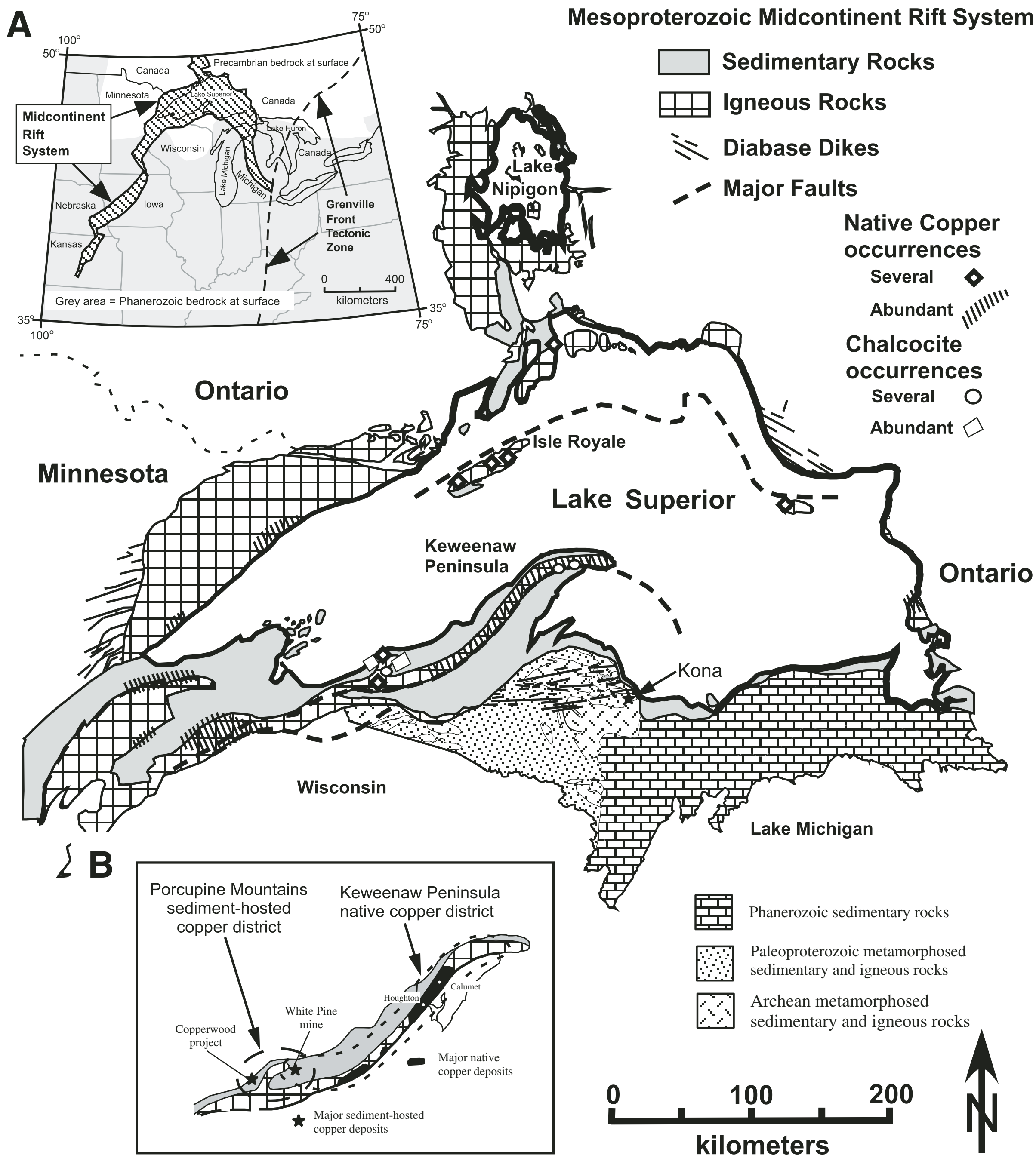


Figure 1. Generalized geologic map of the Upper Peninsula of Michigan and the Midcontinent Rift System of the Lake Superior region. Locations of concentrations of copper in copper-dominated occurrences and deposits are shown around Lake Superior. (A) Overview of the Midcontinent Rift. (B) Outlines of the spatially overlapping Keweenaw Peninsula native copper and Porcupine Mountains sediment-hosted copper districts.

TABLE 1. REPORTED PRE-MINING GEOLOGIC RESOURCE OF COPPER, REGARDLESS OF FEASIBILITY OF MINING, TO ILLUSTRATE THE AMOUNTS OF COPPER CONCENTRATED IN COPPER-DOMINATED DEPOSITS OF THE WESTERN UPPER PENINSULA OF MICHIGAN

| | Reported pre-mining geologic resource (regardless of economic feasibility to mine) | |
|---|---|---|
| | Billions of lbs of copper[1] | Average Cu grade |
| Mesoproterozoic Keweenaw Peninsula native copper district | | |
| Previously mined native copper | 14.4 | 1.84% |
| Unmined native copper | 5.0 | 1.2% |
| Unmined small chalcocite | 0.3 | 2.3% |
| District subtotal: | 19.7 | |
| Mesoproterozoic Porcupine sediment-hosted stratiform copper district | | |
| Previously mined White Pine Mine | 5.9 | 1.14% |
| Unmined Copperwood/Western Syncline | 3.0[2] | 1.45%[2] |
| District subtotal: | 8.9 | |
| Paleoproterozoic Kona sediment-hosted stratiform copper deposit | | |
| Unmined sub-economic | ~1 | ~ 0.5% |
| Western Upper Peninsula of Michigan copper-dominated deposits | ~30 total reported | |

*Note:* These estimates include mined, potentially economic (measured, indicated, and inferred) and potential sub-economic concentrations of copper as reported. For already-mined resources, the estimated pre-mining geologic resource is based on assumption of 85% of the original geologic resource extracted during underground mining and 90% of copper recovered by the mill. Data sources: previously mined copper in the Keweenaw Peninsula from Weege and Pollack (1971) and unmined native copper from unpublished company reports, including measured, indicated, inferred, and potential categories, regardless of feasibility to mine (at least ½ highly likely not feasible to mine); previously mined White Pine Mine from Johnson et al. (1995); measured, indicated (excellent potential to be mined), and inferred for Copperwood/Western syncline from Orvana (2011a, 2011b); and unmined sub-economic potential (unknown probability of feasibility to mine) for Kona from Brown (1986).

[1]Silver is also present in these Mesoproterozoic deposits. At White Pine, an estimated pre-mining geologic resource of silver is 65 million oz and at Copperwood/Western syncline the all categories silver geologic resource is about 12 million oz. The native copper deposits are known to carry native silver along with native copper, but silver was not typically separated during recovery (silver-bearing copper was known as "lake copper"). There is no other metal by-product in these deposits. The silver content of Kona is unknown.

[2]Orvana is working toward converting Copperwood measured and indicated resources (1.096 billion lbs copper at a grade of 1.65% Cu) into reserves (economically and technically feasible to extract).

copper districts host stratiform/stratabound copper deposits in rift-filling volcanic and clastic sedimentary rocks. These deposits were mined from 1845 to 1996 with potential revival of mining in the region as a result of exploration and development activities from 2008 to the present. The Paleoproterozoic Kona Dolomite also hosts significant, but sub-economic, concentrations of stratiform/stratabound copper.

The objectives of this field trip are (1) to develop an understanding of the geologic context of the Mesoproterozoic copper deposits hosted by Midcontinent Rift rocks, and (2) to develop an appreciation of the geologic and human history of the western Upper Peninsula of Michigan.

## BEDROCK GEOLOGY OF THE UPPER PENINSULA OF MICHIGAN

The bedrock geology of eastern part of the Upper Peninsula of Michigan consists of Cambrian to Silurian sedimentary rocks, whereas Precambrian rocks are exposed in the western half of the peninsula (Fig. 1). The Precambrian rocks of the western part of the Upper Peninsula record a long, complicated geologic history, punctuated by three major tectonic episodes (Bornhorst and Brandt, 2009). The oldest episode is Archean in age and culminated with a continental collision forming the Great Lakes Tectonic Zone at ca. 2.7 Ga (Sims et al., 1980). The next episode (Paleoproterozoic) began at ca. 2.3 Ga, with the deposition of sediments in a shallow sea and culminated with a multi-phase collision event called the Penokean orogeny ca. 1.88 Ga (Schulz and Cannon, 2007). The last episode (Mesoproterozoic) occurred between 1.15 and 1.0 Ga with the formation of the Midcontinent Rift and culminated with Grenvillian compression (Cannon, 1994). Multiple episodes of continental glaciations resulted in deposition of unconsolidated Pleistocene glacial-related sediments across the entire Upper Peninsula.

A sub-economic stratiform/stratabound copper concentration is hosted by the Paleoproterozoic sedimentary rocks. The deposition of these sediments began ca. 2.3 Ga on the eroded Archean basement, a rifted continental margin that was submerged under an ocean that deepened to the south (Ojakangas et al., 2001). In Michigan, these Paleoproterozoic rocks are termed the Marquette Range Supergroup and the Kona Dolomite, among the oldest of these rocks, hosts a sub-economic concentration of copper. Stratiform copper sulfide mineralization is within a succession of 6 m of argillite overlain by 9 m of quartzite and capped by 3 m of argillite (Taylor, 1972). The disseminated fine-grained copper minerals (chalcocite, bornite, and chalcopyrite) occur within carbonate cement indicating mineralization is contemporaneous with dolomitization and lithification (Taylor, 1972). This concentration is interpreted to be the result of copper-bearing fluids moving through the middle quartzite and upward and downward into the adjacent argillite beds. There are individual layers within the Kona have grades of 1% over widths of 3 m. The geologic resource is 100 million tons grading 0.5% Cu (Brown, 1986) although it is currently sub-economic. The Kona deposit is best classified as a reduced-facies sediment hosted copper deposit (Cox et al., 2003; Hitzman et al., 2005).

## THE MIDCONTINENT RIFT

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 (Figs. 1 and 2). Beneath Lake Superior, the rift is filled with more than 25 km of basalt-dominated volcanic rocks and 8 km of clastic sedimentary rocks (Cannon et al., 1993), collectively termed the Keweenawan Supergroup (Fig. 3).

About 5 km of rift-filling basalts are exposed in the Keweenaw Peninsula, dominantly the Portage Lake Volcanics (Figs. 2 and 3). 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

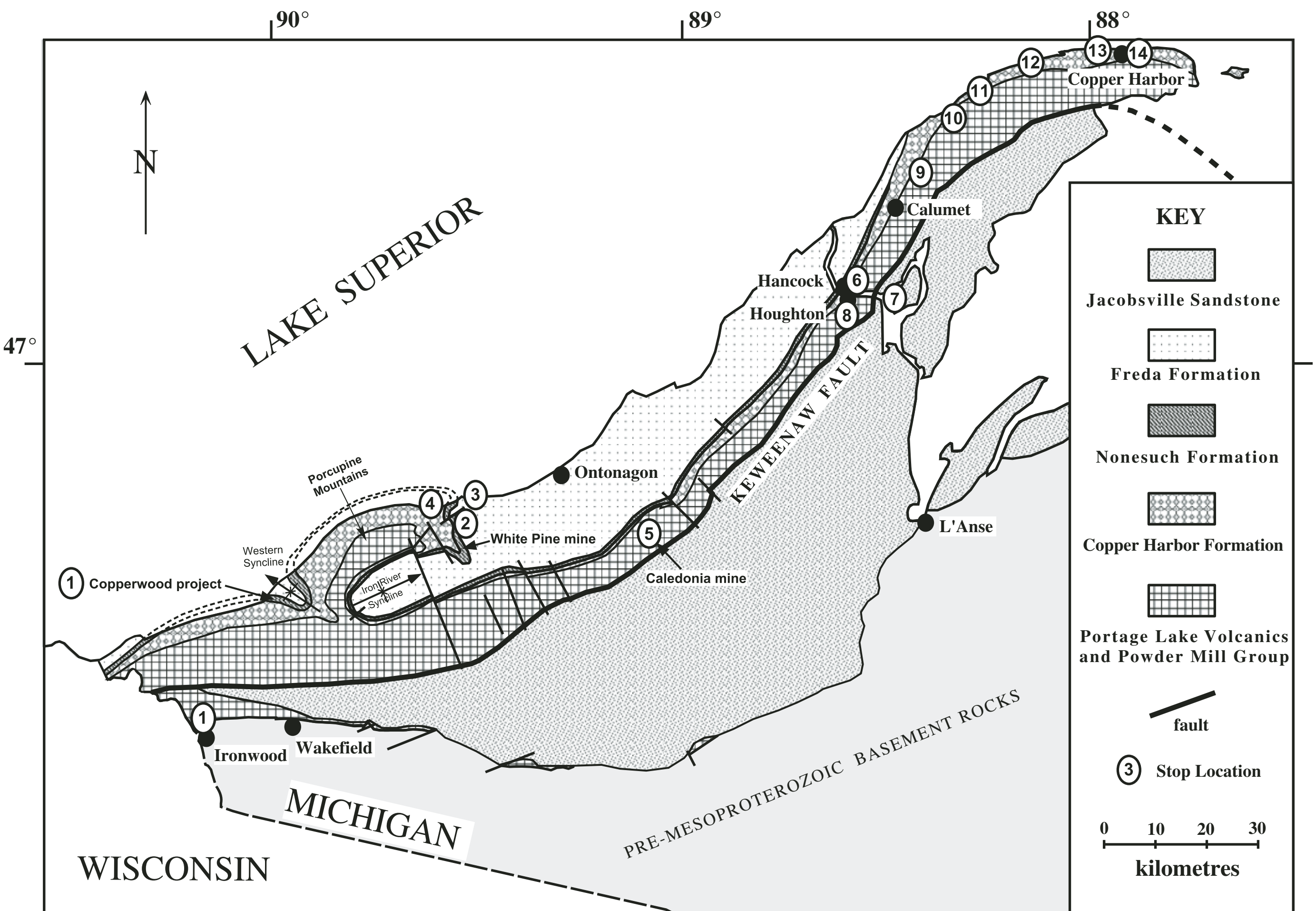


Figure 2. Geologic map of the western most part of the Upper Peninsula of Michigan showing location of field trip stops.

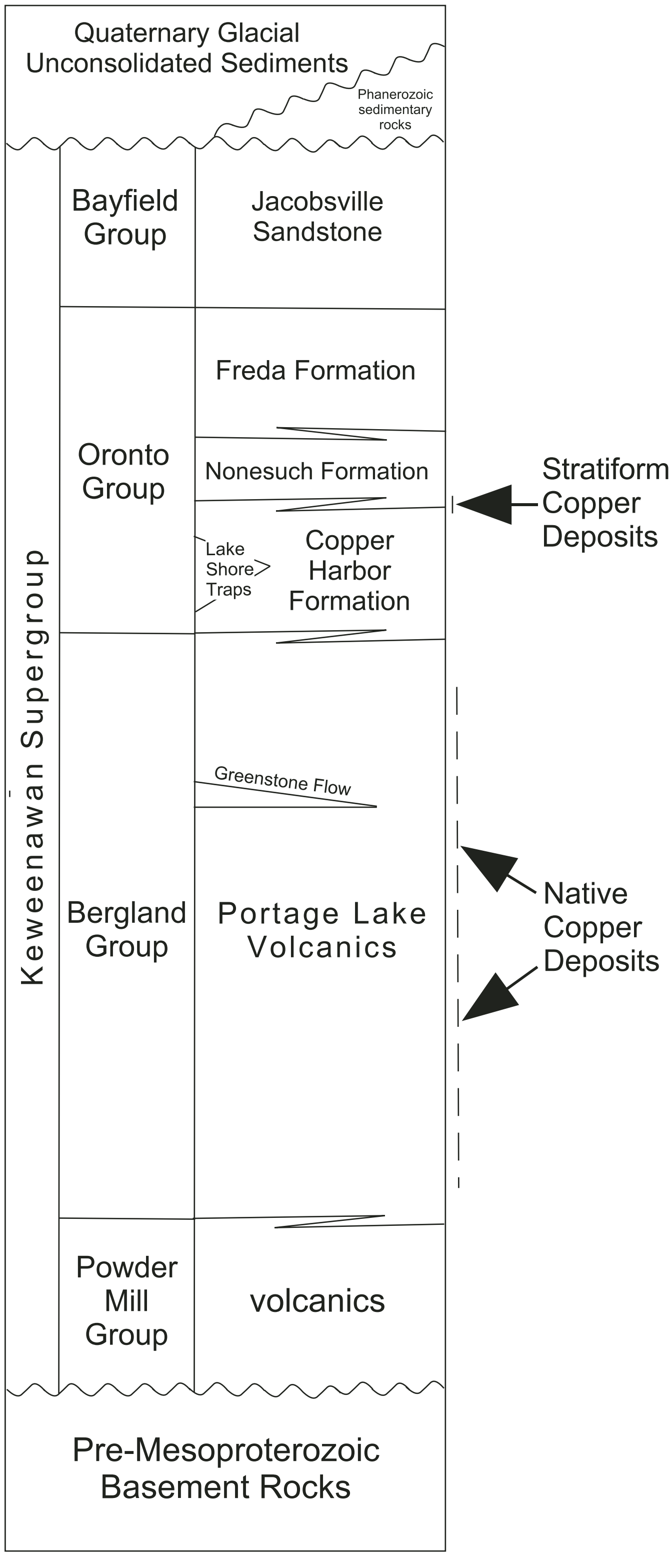


Figure 3. Lithostratigraphic geologic units of the Mesoproterozoic Midcontinent Rift System of Michigan showing the stratigraphic position of more significant copper deposits. Native copper is known to occur in all of the Keweenawan Supergroup of Michigan except the Freda Sandstone.

rift toward the center and deposited on the essentially flat-lying lava flows (Merk and Jirsa, 1982).

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 (Figs. 2 and 3). The Copper Harbor Formation, the oldest rocks of the Oronto Group, are red-brown conglomerates and sandstones deposited in alluvial fans (Elmore, 1984). 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. The overlying Nonesuch Formation consists of gray-to-black siltstones, shales, carbonate laminates, and gray very-fine sandstone. The Nonesuch Formation was deposited in a lake with anoxic to oxic bottom conditions (Elmore et al., 1989). 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 (Cannon, 1994). 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 (Fig. 2). 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 (Fig. 1).

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 breccias clasts (small-to-moderately sized masses weighing up to several lbs and rarely 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 (Butler and Burbank, 1929; White, 1968). 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 (Fig. 4; Weege and Pollack, 1971). 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 (Fig. 4). 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.

Keweenaw Peninsula Native Copper District

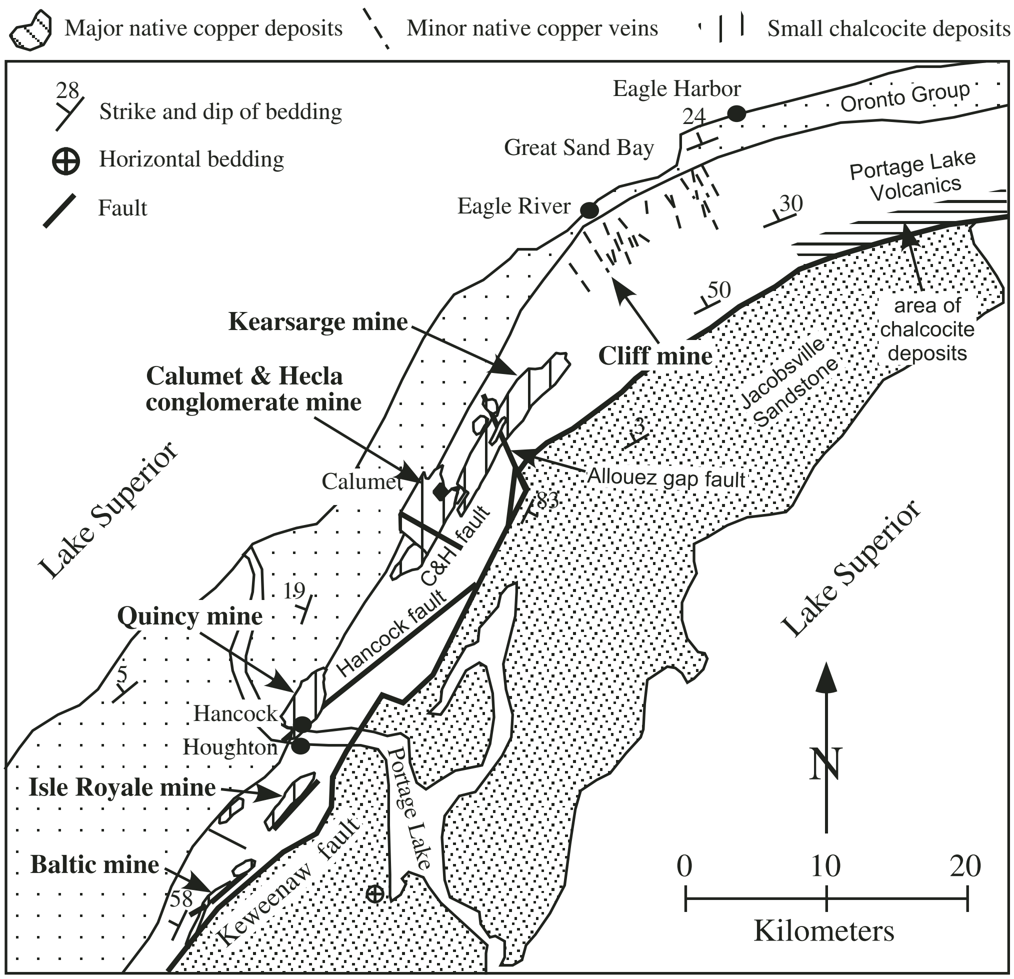


Figure 4. Geologic map of the main part of the Keweenaw Peninsula native copper district, Michigan. The southern extension of the district is shown in Figure 5. All of the native copper mines are hosted by the Portage Lake Volcanics; the areas shown on the map include the mined out down-dip portion projected to the surface

Widespread and Locally Important Hydrothermal Minerals in Native Copper Deposits

albite, adularia, analcime, anhydrite, ankerite, arsenides, barite, calcite, chlorite, chalcocite, datolite, epidote, gypsum, K-Feldspar, laumontite, native copper and native silver, prehnite, pumpellyite, quartz, sericite

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. 4). 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 (Butler and Burbank, 1929; Stoiber and Davidson, 1959; White, 1968). The absolute age of hydrothermal activity is ca. 1.06 Ga (Bornhorst et al., 1988).

Native copper in Keweenawan basalts and interflow clastic sedimentary rocks occurs throughout the exposed Midcontinent Rift (Fig. 1) 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. Figure 4 shows the close connection between cross-cutting faults and the native copper deposits. 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 (Bornhorst, 1997). 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 (Brown, 2006; Bornhorst and Woodruff, 1997; Jolly, 1974; White, 1968). 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 (Bornhorst, 1997).

Copper sulfides are uncommon in the Keweenaw Peninsula native copper district although chalcocite occurs in veinlets cutting the native copper deposits (White, 1968). However, near the tip of the Keweenaw Peninsula, there are 12 small, unmined chalcocite-dominated deposits (Fig. 1). The Gratiot deposit (543-S) is the largest of these containing ~4.5 million tons with an average grade of 2.9% Cu (Maki and Bornhorst, 1999). 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 (Maki and Bornhorst, 1999). 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. Woodruff et al. (1994) and Robertson (1975) suggest that sulfur in these deposits was introduced by hydrothermal mineralizing fluids, but 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.

## PORCUPINE MOUNTAINS SEDIMENT-HOSTED COPPER DISTRICT

Two major sediment-hosted copper deposits and several prospects (Iron River syncline) are located on the exposed margin of the Porcupine Mountains hosted in shales and siltstones of the Nonesuch Formation (Figs. 1 and 2). This district is named herein due to the geographic proximity of the Porcupine Mountains to these deposits. The copper occurs as chalcocite and lesser native copper. Mineralized zones are nearly stratiform. These deposits are examples of the reduced facies or Kupferschiefer subtype (Cox et al., 2003; Hitzman et al., 2005). The White Pine deposit (Figs. 1 and 2) is hosted by shale at the base of the Nonesuch Formation and in the immediately underlying sandstone at the top of the Copper Harbor Formation. About 4.5 billion lbs of copper and 50 million ounces of silver were mined from 1953 to 1996 at an average grade of 1.14% Cu and 0.25 ounces of Ag per ton (Johnson et al., 1995). The Copperwood project deposit in the western syncline (Fig. 2) is hosted by shale at the base of the Nonesuch Formation. About 1.1 billion lbs of copper in 33 million tons of copper-mineralized rock represents the Measured and Indicated Resource at an average grade of 1.65% Cu and 4.3 g/t Ag (Orvana, 2011b). Additional Indicated Resource within the western syncline is 0.77 billion lbs of copper in 27 million tons (Orvana, 2011a).

At the White Pine Mine, ~80% of the stratiform copper is very fine grained chalcocite that occurs as disseminated grains and as concentrations along bedding planes. Native copper occurs as disseminations locally in the top 3 m of Copper Harbor Formation sandstone, within the chalcocite mineralized zones along bedding planes at the base of the Nonesuch Formation, and as sheets along faults. The main ore horizon at White Pine was the chalcocite mineralized lower 5 m of the Nonesuch Formation, in typically black-to-dark gray shales and siltstones. Copper concentrations grade upward from the chalcocite-dominated main ore horizon through a thin fringe zone with djurleite, digenite, bornite and chalcopyrite into pyrite-bearing shale (White and Wright, 1954; Brown, 1971). Chalcocite mineralization at White Pine is characterized as a main-stage stratiform copper mineralizing event that was followed by a second-stage mineralizing event which deposited native copper (Mauk et al., 1992).

At Copperwood, all of the reported copper occurs as chalcocite (Orvana, 2010). The chalcocite mineralized zone is in the lower 3 m of the Nonesuch Formation that consists of black-to-gray shales and siltstones similar to those at the White Pine Mine. The second stage copper mineralization at White Pine is not reported at Copperwood.

The White Pine copper deposit is bisected by an anticline and a right-lateral strike-slip fault (Ensign et al., 1968; Johnson et al., 1995). Strike-slip faults, thrust faults, and normal faults are present to various degrees throughout White Pine. These faults and folds are mostly related to late rift compression with some hosting sheets of native copper. The abundance of secondary structures at White Pine is in contrast to Copperwood where there is only one reported minor fault (Orvana, 2010, 2011b). The base of the tabular Copperwood deposit is approximated by a simple dipping plane lacking undulations.

Although the base of the Nonesuch Formation is enriched in copper along its entire exposed strike length, deposits and known prospects are restricted to the exposed margin of the Porcupine Mountains. This suggests a basin-scale mineralizing process with local influence by the Porcupine Mountains (edifice of a volcanic structure). The chalcocite mineralization at White Pine formed at low temperatures (<130 °C) during early diagenesis (Brown, 2009; Hitzman et al., 2005; Swenson et al., 2004; Mauk, 1992). In the underlying Copper Harbor Formation, clastic red-bed sedimentary rocks provided the paleoaquifer for the copper-mineralizing ore fluids and the source of the copper. Stratigraphic thinning (basin-marginal) and, to a lesser degree, faulting, likely focused upward movement of mineralizing fluids (Brown, 2009; Swenson et al., 2004; Johnson et al., 1995; White, 1971a). Swenson et al. (2004) ruled out topographic density-flow systems as proposed by Brown (2009). Rather, Swenson et al. (2004) proposed "marginward-directed, compaction-driven discharge of cuperiferous brines." Chalcocite mineralization is more abundant around the Porcupine Mountains volcanic structure which likely played a role in controlling the thickness of sediments during deposition, the later secondary structures such as the White Pine fault, and the movement of fluids during diagenesis. The Michigan deposits are consistent with those elsewhere which are attributed to precipitation during diagenesis from basin-scale, fluid-flow systems, where fluids are focused by basin-marginal, stratigraphic structures and faults. Overall, the copper was mobilized from footwall red-bed clastic sedimentary rocks by oxidizing, low-temperature brines and deposited in pyritic, reduced, fine-grained clastic sedimentary rocks (Cox et al., 2003; Hitzman et al., 2005).

The second stage of native copper mineralization at White Pine is closely related with faults and structural planes and is interpreted as being generated by the Grenvillian compression event (Johnson et al., 1995). Thus, second-stage mineralizing fluids and processes likely originated in the same way as those of the Keweenaw Peninsula native copper district (Bornhorst, 1997). A lack of significant fault structures at Copperwood may be the reason no native copper mineralization is reported.

## POST COPPER MINING GEOLOGIC EVENTS

Following the deposition of the copper deposits, the western Upper Peninsula of Michigan was subjected to an extended period of erosion from ca. 1000–500 Ma. During this period, several kilometers of rock were removed exposing the copper deposits at the surface. Supergene alteration generated cuprite, tenorite, malachite, and chrysocolla. The copper ores were subsequently buried by late Cambrian to middle Jurassic sandstones, shale, and limestone (Catacosinos et al., 2001). Another period of erosion and non-deposition occurred from the middle Jurassic to the Pleistocene (ca. 2 Ma). Pleistocene continental glaciation, began ca. 2 Ma and ended at 10,000 yr B.P., at which time the copper ores were once again exposed at the surface and likely at the same erosional level as at the end of the Precambrian (Bornhorst and Robinson, 2004) .

## MINING HISTORY

The mining history of the copper deposits has been summarized here from Bornhorst and Lankton (2009). 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 it, 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. 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.

Copper in and around the future White Pine Mine had been discovered in the 1860s. During the Korean War, in the early 1950s, the U.S. government awarded Copper Range Company a loan to boost domestic copper production, and the company began large-scale mining near the site of the former Nonesuch Mine. Production from the White Pine Mine quickly eclipsed output from the surviving native copper mines. The White Pine Mine production peaked in 1975 at 183 million lbs. The mine closed in 1981 but reopened in 1986 with government support. After four decades of mining, the White Pine Mine permanently closed in 1996.

In November of 1954, work published by the U.S. Geological Survey (White and Wright, 1954) led to discovery of mineralization comparable to White Pine in the western syncline. This led to exploration and a test shaft in 1957 (Orvana, 2010). In 1959, active exploration ceased and subsequent attempts to restart exploration were not successful until 2008. Orvana Minerals Corporation began active exploration for copper at what was now called the Copperwood project with extensive drilling and reported a Canadian National Instrument 43-101 compliant Measured and Indicated copper resource in 2010 that was subsequently updated in 2011. The Copperwood project continues to proceed toward becoming a new Michigan copper mine.

## FIELD TRIP STOPS

The field trip leaves from Minneapolis, Minnesota, where the drive will take participants across the Midcontinent Rift on the southwest end of Lake Superior to the first stop at the Ironwood, Michigan offices of Orvana Minerals Corporation. The first day focuses on the Porcupine Mountains sediment-hosted copper district and regional geology with Stops 1 to 4 (Fig. 2). Participants will overnight in Silver City, Michigan. Day 2 and 3 focus on the Keweenaw Peninsula native copper district and regional geology. The Stop 5 at the outset of Day 2 provides an opportunity to see a native copper deposit underground at the Caledonia Mine. Day 2 continues in the Houghton, Michigan, area with Stops 6 to 8, ending the day at the nationally recognized A.E. Seaman Mineral Museum on the campus of Michigan Technological University. Participants will overnight in Houghton, Michigan. Day 3 consists of Stops 9 to 14 (Fig. 2) as the field trip progressively moves towards the east end of the Keweenaw Peninsula and the final stop near Copper Harbor, Michigan, at Fort Wilkins State Park.

### Stop 1. Copperwood Project—Orvana Minerals Corporation

The geology of the Copperwood deposit is described in Canadian NI43-101 reports and is summarized here (Orvana, 2010; Orvana, 2011a, 2011b) (Fig. 2). The deposit is not exposed and will be represented by drill core at the offices of Orvana Minerals Corporation in Ironwood, Michigan.

The sediment-hosted stratiform deposit is located on the western limb of the gently plunging western syncline at the base of the Nonesuch Formation (Fig. 3). The mineralized zone at Copperwood is stratigraphically equivalent to the White Pine Mine. While the stratigraphic sub-units at Copperwood and White Pine are quite similar, their thicknesses are different. The rocks of the western syncline stratigraphically encompass the top of the Copper Harbor Formation, all of the Nonesuch Formation, and the base of the Freda Formation (Fig. 3). In the area of Copperwood, the rock units dip about ~10° with the base of the Nonesuch approximated by a simple plane lacking undulations. There is only one documented minor fault. Bedrock is covered by roughly 30 m of unconsolidated glacial sediments.

Copper mineralization at Copperwood is hosted exclusively in three conformable sub-units at the base of the Nonesuch Formation, collectively termed the copper-bearing sequence (CBS). Chalcocite is the only reported sulfide-bearing mineral and occurs as disseminated grains ranging in size from 5 to 50 microns and as concentrations along bedding planes. The CBS averages 2.7 m thick in the main part of the deposit and 2.0 m thick in the adjacent section 6 part. The principal copper host within the CBS is a black shale, termed domino, with an average thickness of 1.6 m in the main part of the deposit. In the main part of the deposit the domino hosts ~70% of the Measured and Indicated copper resource and averages 2.58% Cu. Overlying a domino is the red massive sub-unit consisting of reddish colored siltstone and fine sandstone, and averaging 0.3 m thick in the main part of the deposit with 0.39% Cu. The top of the CBS is composed of gray laminated siltstones, termed gray laminated, which averages 1.0 m thick with 1.32% Cu in the main part of the deposit. In the main part of the deposit, the red massive and gray laminated sub-units have been combined into the upper CBS and host ~30% of the main Measured and Indicated copper resource. Silver is the only other potentially economic metal. The CBS averages 6–7 g/t (ppm) in the main part of the deposit. The total reported Canadian National Instrument compliant Measured and Indicated Resource for the Copperwood deposit (main and S6) is 30.1 million metric tonnes averaging 1.65% Cu or a total in situ resource of 1096 million lbs Cu and 4.3 ppm Ag (Orvana, 2011b).

### Stop 2. Nonesuch Formation along the Big Iron River at Bonanza Falls

***Directions:*** Take U.S.-2 east to the Wakefield intersection. Turn left and head northeast on M-28 for 20 mi (32.2 km) to Bergland. Turn left (north) on M-64 and drive 17 mi (27.4 km) to a road on left which takes you to Bonanza Falls along the Big

Iron River. Park and then hike a short distance to the Nonesuch exposure. [UTM 5187882 N 160303947E (NAD27 CONUS)]

A stratigraphic section, ~244 m thick, of Nonesuch Formation is exposed along the Big Iron River near Bonanza Falls (Fig. 2). This locality is close to the White Pine Mine where the base of the Nonesuch Formation was mined for contained copper. This is a nearly complete section of the Nonesuch Formation except for the lower and upper contacts. The beds of the Nonesuch dip moderately to the southeast. Suszek (1991) has studied the stratigraphy of the Nonesuch Formation and measured this section along the Big Iron River.

The Nonesuch Formation is characterized by gray, green, and black fine-grained clastic sedimentary rocks, readily distinguished from other Keweenawan red-bed sediments. Along the Big Iron River, the Nonesuch consists of siltstone and fine sandstone with minor shale. Many of the rocks show symmetrical and asymmetrical ripple marks, trough cross-bedding, and parting lineations. Well-laminated shale is most abundant in the lower part of the section. Shaly units have calcareous concretions and ball and pillow structures. Normally graded sequences are common in units from cm to a few m thick. The bottom 10 m of the section contains very fine-grained chalcocite and supergene malachite. The best section showing stratiform mineralization cannot be accessed without crossing the river.

### Stop 3. Freda Formation along M-64

***Directions:*** Continue driving north on M-64 to Highway 107. Turn right (east) on Highway 107 and continue 1.3 mi (2.1 km) to road a small low profile roadside outcrop. [UTM 5189788N 160306262E (NAD 27 CONUS)]

The Freda Formation is exposed along M-64 and the Lake Superior shore line in this area (Fig. 4). The Freda consists of reddish brown, fine- to coarse-grained, micaceous, lithic sandstone with occasional pebbly layers. The Freda Formation is volumetrically the dominant rift-filling sedimentary unit with an exposed thickness of over 4000 m along the margin of the rift and possibly is even thicker under Lake Superior. The Freda Formation was deposited in a fluvial environment.

### Stop 4 (optional). Copper Harbor Formation at Union Bay

***Directions:*** Continue driving north on M-64 to M-107. Turn left (west) from Stop 2 on M-107 and continue 1.6 mi (2.6 km) to turn off to Union Bay on right. Park in the campground area, and walk to the shoreline to see the exposure of the Copper Harbor Formation. [UTM 5188274N 160298908E (NAD 27 CONUS)]

The Copper Harbor Formation is exposed along the Lake Superior shoreline at Union Bay (Fig. 2). The exposures at Union Bay consist of reddish sandstone with minor conglomerate dipping 10–20° to the north. The sandstones show oscillation and current ripples, trough cross-bedding, desiccation cracks, and rip-up clasts. These exposures are in the upper part of the Copper Harbor. In general, the Copper Harbor Formation is characterized by coarse volcaniclastic conglomerates in the lower part of the unit, grading upward into sandstone with minor conglomerate deposited in a pro-grading alluvial fan.

Sandstones of the Copper Harbor Formation are overlain by shales and siltstones of the Nonesuch Formation which host copper mineralization at the Copperwood deposit and the White Pine Mine (Fig. 3). At the nearby White Pine Mine, native copper forms the cement in the sandstone of the uppermost Copper Harbor Formation.

### Stop 5. Caledonia Mine

***Directions:*** Leave Silver City on M-64 and drive east to the intersection M-38. Take M-38 southeast to Ridge Road. Turn right (south) on Ridge Road, which turns into Caledonia mine Road. Drive southwest 1.7 mi (2.7 km) to the Caledonia Mine. The Caledonia mine is privately owned and permission is required to enter this property. [UTM 5179684N 160338022E (NAD27 CONUS)]

The Caledonia Mine, owned by Red Metal Minerals, is located near Mass, Michigan (Figs. 2 and 5). The Caledonia Mine provides rare access to underground native copper mineralization as most of the native copper mines of the Keweenaw Peninsula are closed permanently and flooded. Copper mineralization at the Caledonia Mine is part of the southwestern extension of the district, some 40 km from the major producing mines along the Keweenaw Peninsula (Fig. 1). The Caledonia Mining Company commenced operations in 1863 and continued mining sporadically until 1881. In 1937, Calumet and Hecla Consolidated Copper Company (C&H), the major producer in the Keweenaw Peninsula native copper district, began an evaluation program which estimated 1.45% Cu in the ore of Caledonia's Knowlton lode. This project was stopped because of World War II. In 1950, C&H removed a 200 ton bulk sample, commenced mining in 1951, and continued through 1958. Red Metal Minerals acquired the mineral rights in 1985 from Copper Range Company. Currently, the Caledonia Mine is operated as a specimen mine and for educational activities. In total, the mine has yielded ~6.8 million lbs of refined copper.

There are a number of mines along a total strike length of ~5 km within this southwestern extension of the native copper district (Fig. 5). These mines extracted copper from mineralized lava flow tops that are part of the informal Evergreen series within the Portage Lake Volcanics. The Evergreen series consists of multiple subaerial basalt lava flows (up to 210 m in total thickness) that dips ~45° northwest toward Lake Superior. Between the Mass and Adventure mines, the strike of these flows changes ~35° from N70°E to N35°E. Thus, mines are situated around this anticlinal bend. Many veins and faults are sub-perpendicular to the strike of bedding; only a few faults have displacements of more than 1 m, so the stratigraphy is easy to reconcile. Most of these mineralized veins are in tension fractures related to bending. Some veins are parallel to strike but dip in the opposite direction. The basalt flow tops are fragmental amygdaloids (brecciated flow tops) and the best grades of native copper are in thicker fragmental zones.

At the Caledonia Mine native copper is hosted by a fragmental top of a lava flow informally called the Knowlton flow. The most abundant gangue mineral is calcite, filling amygdules and spaces between fragments. It is followed by nearly equal amounts of quartz, epidote and red K-feldspar. There are lesser amounts of prehnite, pumpellyite, and chlorite. Native copper is present in small amounts with an average grade of ~1.45% Cu. Native silver and datolite are present in much lesser amounts. Least abundant are laumontite, adularia, and the clay mineral, corrensite. K-feldspar is an early formed mineral followed by epidote and then datolite, prehnite, pumpellyite, chlorite, calcite and quartz. Native copper is found as inclusions in epidote, calcite, quartz, and datolite. Late-stage minerals include calcite (second episode of deposition), laumontite, adularia, and corrensite. No major differences exist in the abundance of secondary minerals averaged over the scale of hundreds of meters. In some areas, secondary minerals display banding consistent with progressive filling of open spaces. The intensity of alteration is highest near both the hanging wall and footwall of the brecciated flow top lode. Native copper tends to be more commonly associated with epidote, calcite, and quartz. Rarely is native copper abundant in areas with abundant K-feldspar. In general, the grade of copper is highest where the fragmental amygdaloid is thick, forming ore shoots. Thinner zones are lean or barren. Rich pockets of ore sometimes occur near the footwall of the lode, often in highly epidotized basalt. These footwall pockets are associated with strike parallel veins that extend into underlying massive basalt and are considered synchronous with lode formation. Such veins in the Caledonia Mine are quite similar to those described by Broderick (1931) in the Baltic and Isle Royale Mines ~50 km northeast near Houghton and are interpreted as pathways for ascending hydrothermal fluids. Late-stage veins that crosscut the native copper mineralized lode, containing calcite, laumontite, and adularia are barren and deposited at lower temperature than native copper and related minerals. Alteration due to the movement of meteoric ground waters is noticeable in some parts of the lode. Especially notable is the occurrence of tenorite coating on native copper. Overall, the native copper mineralization style

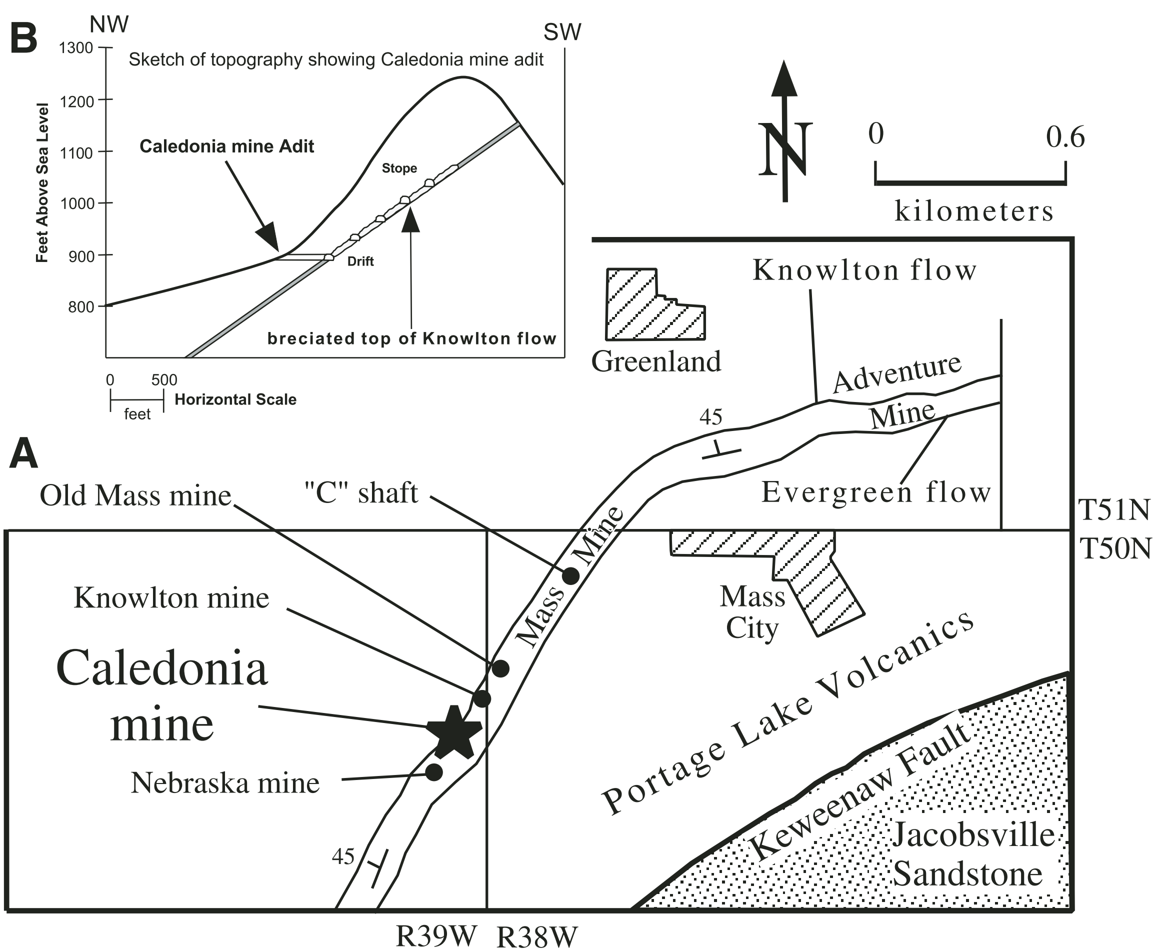


Figure 5. (A) Geologic setting of the southwestern extension of the Keweenaw Peninsula native copper district, Michigan. (B) Cross section sketch of the Caledonia Mine.

and paragenetic sequence observed at the Caledonia Mine can be considered representative of the district as a whole (Bornhorst and Whiteman, 1992).

**Stop 6. Quincy Mine, Keweenaw Heritage Site of the Keweenaw National Historical Park**

***Directions:*** Leave Caledonia Mine and follow road back to M-38. Turn right and head northeast on M-38/M-26 for 38 mi (61 km) to the bridge intersection in Houghton. Merge left onto U.S.-41 north. Cross the bridge to Hancock and follow U.S.-41 north for 2 mi (3.2 km) to the Quincy Mine No. 2 shaft house on right side of road. [UTM 5221556N160380546E (NAD27 CONUS)]

The Quincy Mining Company, incorporated in 1848, opened nine shafts on the Pewabic lode and operated until 1967 (Figs. 2 and 4). 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 (Butler and Burbank, 1929). 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. The nonprofit Quincy Mine Hoist Association, Inc., currently owns and operates the Quincy Mine properties. Daily guided tours are available of several important surface buildings. The Quincy Mine historical site also provides the option for visitors to go take an underground tour (not provided for this GSA field trip). The tour utilizes a 700 m long adit that connects to the No. 5 shaft at the 7th level and old early excavations. This facility is a Keweenaw Heritage Site of the Keweenaw National Historical Park. The Keweenaw Historical National Park was established in 1992 to preserve historical and cultural sites and to interpret the story of copper on the Keweenaw Peninsula through the interaction of geological, aboriginal, sociological, cultural technological, and corporate activities.

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 U.S.-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. Field trip participants will be able to see inside the No. 2 shaft house, and an informative video provides more information about it.

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 (Molloy, 2007). 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. The boulder is displayed on a unique one-of-a-kind hydraulic stand built by Royale Inc. in Calumet, Michigan. 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. The geology of the discovery is discussed at Stop 11.

**Stop 7. Jacobsville Formation along M-26 near Tamarack**

***Directions:*** Leave motel to U.S.-41 north. While crossing the bridge, stay in the right lane to M-26 north to Ripley/Dollar

Bay. Drive 5 mi (8.1 km) to roadside outcrops. [UTM N 5222120 E 16038915 (NAD27 CONUS)]

The Jacobsville Sandstone is a red-bed succession consisting of feldspathic and quartzose sandstones, conglomerates, siltstones, and shales up to 1000 m thick that were deposited by fluvial processes in a rift-flanking basin (Fig. 2). Overall, there are no interbedded lava flows nor cross-cutting dikes and thus, the age of the Jacobsville Sandstone is inferred to be ca. 1060–1020 Ma. Jacobsville sedimentation was the last Precambrian event associated with the development of the Midcontinent Rift.

The Jacobsville Sandstone at this stop displays features characteristic of the unit as a whole. At the northeastern end of the outcrop, reddish shale and red-brown siltstone are exposed at the highway level. They are overlain by two fining-upward sequences of conglomerate and red, red-brown, and white cross-bedded sandstone. The lower conglomeratic bed is planar and can be traced 30 m to the southwest, along with the directly underlying shale and siltstone. Farther to the southwest, the section is almost entirely cross-bedded red sandstone; some beds are contorted and mottled. The sandstone consists of almost equal parts of rounded-to-sub-rounded quartz, feldspars, and lithic fragments. Clasts in the lower conglomerate are predominately sub-angular, and rhyolitic in composition, with subordinate mafic volcanic rocks.

Mining history will be viewed along M-26 from Mason to Lake Linden as an extension of the actual Stop described above, history summarized here from Molloy (2007). The Quincy Mining Company built a reclamation plant in 1942–1943 to reprocess the stamp sand tailings along Torch Lake, and from 1943 to 1967 recovered ~50,000 tons of copper. One of the mining dredges used in the recovery process sank in a storm in 1956 and is located just offshore. The foundations between the road and the dredge are part of the Quincy Mills for processing native copper ore. About 2 mi (3.2 km) from the Quincy Mills, is the only remaining steam stamp that was part of the Ahmeek Mill. The steam-driven stamp hammers could deliver ~104 blows per minute and process 7000 tons of ore a day. Another 0.75 mi (1.2 km) toward Lake Linden are the remains of the Calumet and Hecla (C&H) smelter. C&H was the largest native copper producer in the district. The large building at the north end of the site next to the highway was the C&H mineral storage building where crushed and concentrated copper ore was smelted. It is now occupied by Peninsula Copper Industries which primarily recovers copper from scrap copper such as printed circuit boards to make copper sulfate as a fungicide for the wood preservative industry and to make other specialty copper compounds. Just before entering Lake Linden on the right is the C&H Mill. The C&H Mill was first built in 1867 with several expansions as milling practices changed and closed in 1956. Like Quincy, C&H also reclaimed copper from the sand tailings. The Houghton County Historical Museum is located on the edge of Lake Linden and exhibits mining and local history.

**Stop 8. A.E. Seaman Mineral Museum, Michigan Technological University**

***Directions:*** Proceed south on U.S.-41 through Houghton and adjacent to the campus of Michigan Technological University until the traffic light. Turn right at the light on Macinnes Drive. Follow MacInnes Drive (merges into Sharon Avenue) 1.1 mi (1.8 km) to the Seaman Museum, 1404 E. Sharon Avenue on the campus of Michigan Technological University. [UTM 5218645N 160382198E (NAD27 CONUS)]

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.

**Stop 9: Allouez Conglomerate at Bumbletown Hill and Overlook**

***Directions:*** From Houghton, follow U.S.-41 north to Calumet. Continue on U.S.-41 3.6 mi (5.8 km) past the headquarters of the Keweenaw National Historical Park denoted by a park sign and a large specimen of glacial float native copper to Bumbletown Road and turn left (west). Drive ~0.4 mi (0.6 km) to rock pile. [UTM 5237960N 160393345E (NAD27 CONUS)]. To access the overlook, leave the rock pile and continue on Bumbletown Road west ~0.5 mi (0.8 km) to overlook at the top of the hill near towers. [UTM 5238215N 160392860E (NAD27 CONUS)]

The Allouez conglomerate (informal member) is one of a small number of interflow clastic sedimentary horizons within the Portage Lake Volcanics. This particular conglomerate bed can be traced along strike from the tip of the Keweenaw Peninsula, to at least the Mass area (near Stop 5), a strike length of more than 120 km (Fig. 2). The Allouez conglomerate is stratigraphically just below the Greenstone flow, arguably the largest basalt flow in the world, within the Portage Lake Volcanics. The rock piles at the base of Bumbletown Hill are from the Allouez Mine. The Allouez conglomerate consists of mostly red-colored conglomerate with lesser amounts of sandstone and siltstone. The largest contained boulders at this locality are ~65 cm in diameter and the median size is ~8 cm. A pebble count of boulders more than 20 cm across gave the following results: mafic rock, mostly amygdaloidal basalt, 16%; quartz porphyritic rhyolite, 36%; feldspar porphyritic rhyolite, 11%; and granophyre, 37% (White, 1971b).

The mines on the Allouez conglomerate yielded only ~75 million lbs of refined copper. Some evidence of native copper mineralization can be seen in rocks at this stop. Occasionally, one can find a specimen with native copper filling the void space between clasts and grains. Calcite and chlorite are the dominant pore-filling secondary minerals visible on this rock pile. Thin black veinlets cutting the Allouez conglomerate consist of calcite with chalcocite "dust." While supergene alteration resulting from the downward percolation of groundwater is not common in most the native copper deposits, at this stop, supergene alteration minerals are common including chrysocolla, malachite, and cuprite.

From the overlook on a clear day, Isle Royale may be seen 80 km to the northwest and the Huron Mountains may be seen beyond Keweenaw Bay, 60 km to the southeast. The land slopes very gradually to the northwest toward Lake Superior, as it does throughout most of the length of the Keweenaw Peninsula. The area is underlain mainly by conglomerates and sandstones of the Copper Harbor Formation dipping at ~20°. The southeastern flank of the Keweenaw Peninsula has a steeper slope at the skyline, following approximately the line of the Keweenaw fault. The low-lying plain between the fault and Keweenaw Bay, is underlain by flat-lying Jacobsville Sandstone.

Bumbletown Hill is located on the southwest side of the Allouez Gap, a NW- to SE-trending valley. The valley follows the Allouez Gap fault, a zone of faults and fractures, along which the Portage Lake Volcanics and Keweenaw fault are offset. At this gap, the strike of the Portage Lake Volcanics swings from about N35°E to N50°E (Fig. 4). Almost every permeable horizon near the Allouez Gap fault contains above average amounts of native copper; nowhere else in the district are there so many mineralized beds. About 60% of the district production can be linked to the fault as a primary pathway for ore fluids. The fault bisects the Kearsarge deposit, which was the second largest copper producer in the native copper district. The line of rock piles demarking the many mines along the Kearsarge deposit is a little more than 1500 m southeast of Bumbletown Hill. The Kingston Mine, a small deposit that produced 20 million lbs of copper (1963–1968; one of the most recent native copper mines to open and last to close), is bisected by the Allouez Gap fault. About 1200 m N65°E of the hilltop, the Houghton conglomerate and the Iroquois flow produced 33 million lbs of copper.

Looking northeast along the strike of the Portage Lake Volcanics, one can see the cuesta form of the ridge upheld by the Greenstone flow. To the right of the ridge, the more distant hills are formed by lava flows lower in the Portage Lake Volcanics sequence. At Bumbletown Hill, the Greenstone flow is only 85 m thick, but the flow thickens abruptly to more than 400 m near end of the cuesta ridge. It dips northward at ~25° toward the center of the Lake Superior. The Greenstone flow can be traced along much of the Keweenaw Peninsula and has been stratigraphically and geochemically correlated with a similar unit on Isle Royale, 90 km away, on the opposite side of the rift. Thus, the areal extent of this great flow exceeds 5000 $km^2$, and its volume is on the order of 800 to1500 $km^3$ (Longo, 1982). The geochemical composition of the Greenstone flow magma is more evolved than typical olivine tholeiites of the Portage Lake Volcanics.

**Stop 10. Cliff Mine Rock Pile**

***Directions:*** Take Bumbletown Road back to U.S.-41 and turn left (northeast). Continue 1.2 mi (1.9 km) to Cliff drive, which makes a slight left. Continue ~7.5 mi (12.1 km) to the Cliff Mine site on the left. [UTM 52247173N 160400875E (NAD27 CONUS)]

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 ~38 million lbs of refined copper (Figs. 2 and 4). 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 calcite, epidote, chlorite, laumontite, prehnite, datolite, chlorastrolite, apophyllite, and adularia.

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 Midcontinent Rift (Butler and Burbank, 1929). The steep ridge near the Cliff rock pile is the Greenstone flow (see also Stop 9). Here it makes up the entire high ridge from bottom to top and with a northward dip of ~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 11. Great Sand Bay Overlook**

***Directions:*** Continue driving northeast on Cliff Drive for a short distance until it intersects U.S.-41. Turn left on U.S.-41 to the Phoenix intersection of U.S.-41 and M-26 then turn left. Continue 7 mi (11.3 km) on M-26 through Eagle River until the Great Sand Bay overlook. [UTM 5253974N 160406985E (NAD27 CONUS)]

The Great Sand Bay overlook provides a beautiful view of Lake Superior (Figs. 2 and 4). At the road level, the sand dunes are remains of the Lake Nipissing Stage (4000–5000 years ago) as glacial waters receded toward their present level. The underlying bedrock is the Copper Harbor Formation. In the Keweenaw

Peninsula there is a succession of basalt lava flows interbedded near the middle of the formation (see Stop 12). The massive interiors of these lava flows are more resistant to erosion than the underlying and overlying conglomerates and sandstones of the Copper Harbor Formation. As a result, harbors such those at Eagle Harbor and Copper Harbor are maintained by lava flows visible at their mouths. While not visible, lava flows occur at the mouth of Great Sand Bay too.

There are many extensive underwater fissure vein deposits which cross cut the Eagle River shoals located ~0.5–1 km offshore. Many of them are often quite rich in native copper and can contain long continuous stringers protruding up to 1.5 m in height and extending almost 6 m in length. Most of veins are less than 50 cm in width and are primarily composed of quartz or calcite with minor amounts of laumontite, datolite, prehnite, and traces of silver. Veins will locally contain clay pockets which can produce well defined copper crystal specimens. The largest copper specimen ever recovered underwater was a massive 17 ton unattached copper boulder in July of 2001. It was recovered from one of these vein deposits north of Jacobs Creek in ~9 m of water (see also Stop 6). To date, there have been 36 underwater copper veins discovered from the eastern tip of Great Sand Bay to Eagle River, ~3.2 km west.

**Stop 12. Lake Shore Traps (Copper Harbor Formation) at Esrey Park**

***Directions:*** Continue driving 8.3 mi (13.4 km) northeast on M-26 through Eagle Harbor until arriving at the Esrey Park turn off on left. [UTM 5257600N 160420430E (NAD27 CONUS)]

The basalt flows cropping out at Esrey Park are a part of a succession of Fe-rich olivine tholeiite, basaltic andesite, and andesite lava flows known collectively as the Lake Shore Traps (an informal member within the Copper Harbor Formation; Fig. 2). These represent the waning stage of volcanism within the Midcontinent Rift and have been dated at 1087.2 ± 1.6 Ma (Davis and Paces, 1990). The lowermost mafic flows were deposited as ponded sheets while upper andesite flows may have formed a low, positive topographic feature such as a shield volcano. The large outcrop between the parking lot and the shore is a massive flow interior of fine-grained, Fe-rich olivine tholeiitic basalt. The flow strikes parallel to the shoreline and dips 20–30° toward the lake. The upper portion of this flow is not exposed, but the top of the underlying basalt flow can be seen at the shoreline on either side of the large outcrop. This well-exposed flow top is composed of vesicular basalt, typical of a pahoehoe flow top. Because of its geographic location (further from the mines) and stratigraphic position (higher in the section), the hydrothermal alteration in the Lake Shore Traps is lower temperature (zeolite facies) than in the heart of the native copper district. At Esrey Park, secondary minerals include agate, chalcedony, quartz, laumontite, analcite, calcite, and smectite in amygdules. Massive flow interiors of the Lake Shore Traps often retain relict olivine and interstitial glass in contrast to the Portage Lake Volcanics, where both olivine and interstitial glass are invariably replaced by Mg-Fe phyllosilicates.

**Stop 13. Copper Harbor Formation at Hebard Park**

***Directions:*** Continue driving 5.4 mi (8.7 km) east on M-26 until arriving at the Hebard Park conglomerate exposure on left. [UTM 5258659N 160428890E (NAD27 CONUS)]

The Copper Harbor Formation is exposed along the Lake Superior shoreline at Hebard Park (Fig. 2) and is stratigraphically above the Lake Shore Traps (Stop 12). The lithologies at this stop consist of interbedded conglomerates and sandstones that characterize the Copper Harbor Formation. Clast-supported conglomerate beds consist of rounded, cobble- to boulder-sized clasts with a matrix of coarse sand-sized subangular grains cemented with carbonate and iron oxide. Clasts are predominantly of silicic volcanic rocks, with subordinate basalt, pyroclastic, plutonic, and metamorphic rocks. Several finer grained interbeds higher in the exposed section exhibit crossbeds, current lineations, current ripples, parting lineation, and reduction spots. In particular, one should note the calcite-rich cemented zones that may represent vadose carbonate or paleocaliche (Kalliokoski, 1986). There is a thin continuous zone of laminated cryptoalgal carbonate, laterally-linked stromatolite that is draped over cobbles and contorted layers in mudstone-siltstone.

**Stop 14. Fort Wilkins Historic State Park**

***Directions:*** Continue driving east on M-26 4.6 mi (7.4 km) until arriving at entrance to Fort Wilkins State Park on right. [UTM 5257338N 160434763E (NAD27 CONUS)]

Fort Wilkins was built in 1844 by the U.S. Army to provide order on the Keweenaw frontier and to protect the copper resources during the Civil War (Fig. 2). The army built 27 structures to house two full strength infantry divisions. After the soldiers were needed in the Mexican War in 1846, the fort was abandoned. Fort Wilkins became a state park in 1923. During the 1930s under the Work Project Administration, the fort underwent extensive restoration. Many of these structures still survive today and have been either been restored or rebuilt after archaeological excavations. Today, the restored buildings contain exhibits on the mining history of the area.

Considerable exploration activity took place in the immediate vicinity of the fort, and there are shafts and exploration pits between Lake Fanny Hooe and the harbor, mostly from exploration during the period from 1843 to 1846. Just north of the park store, several pits provide evidence of early mining activity by European settlers. The Pittsburgh and Boston Mining Company operated here in the 1840s on a vein of native copper within the Copper Harbor Formation; the vein was reported to be up to 0.3 m wide. This venture was not profitable.

Opposite Fort Wilkins is a view of the Copper Harbor lighthouse, one of the first on Lake Superior built in 1866. Near the lighthouse on the Lake Superior shoreline is the famous "green rock." The green rock is a vein that was described by Douglass Houghton. Houghton himself may have never really understood the uniqueness of the district. Conventional wisdom at the time led him to the interpretation that the green rock was the surficial alteration of a sulfide ore (Krause, 1992). Nevertheless, Houghton had a profound impact in promoting the district. He drowned in 1845 near Eagle River, Michigan, while leading a geological expedition.

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