

## Keweenaw Peninsula (USA)

**Description:** Keweenaw is the World's largest native copper mining district, from which about 6 million tons of refined copper was extracted between the years 1845 and 1968. The district is situated on the Keweenaw Peninsula on Lake Superior, northern Michigan, in the United States (Figure 1). During the operational period, copper was excavated from more than 20 different mines within the roughly 50 km long main ore-producing belt. A related mine, White Pine, is situated about 90 km southwest of the main copper district.

Native copper deposits are hosted in Middle Proterozoic (1.1 Ga old) Portage Lake Volcanics (PLV), forming an approx. 2.5 – 5.2 km thick sequence of lava flows. The rocks stratigraphically above the PLV are sediments, ranging from conglomerate to shales (Nonesuch shale). Sandstones are common components of the Keweenawan Supergroup both below (Jacobsville-) and above (Freda Sandstone) the volcanic sequences (to which also the 'unnamed' formation belongs). The rock strata are folded so that the peninsula forms an anticline bordered by synclines on both sides. However, due to the presence of the Keweenaw Fault, the original thickness and stratigraphic base of the PLV is not known.

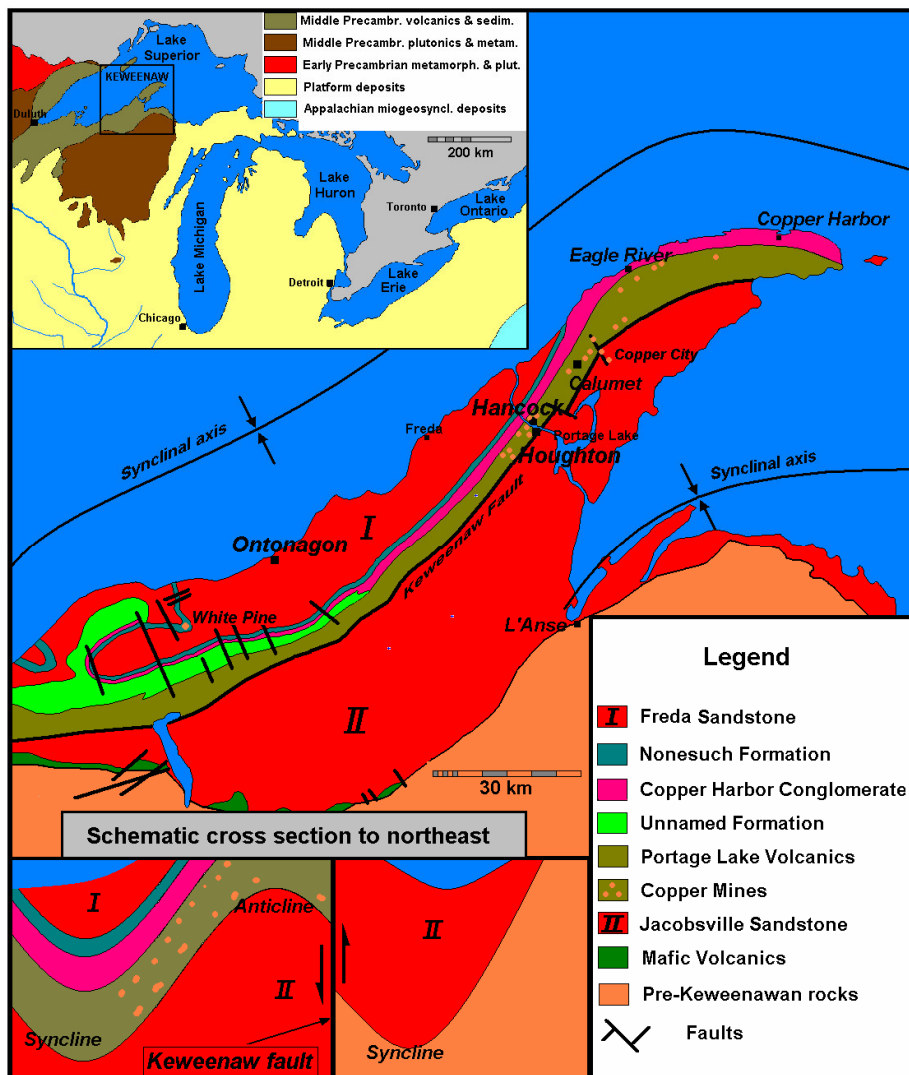


Figure 1. Location and geology of the Keweenaw native copper district. The figure is compiled from Morey et al. (1982), King (1967) and Bornhorst et al. (1983).

Extrusion of the Portage Lake lava flows was associated with the formation of a mid-continent rift, which extends from Lake Superior across the Central U.S. to Kansas, but which is mainly blanketed by younger Platform deposits. With continued opening of the rift and associated volcanic eruptions, the lava pile grew in thickness and was subsequently buried in the gradually subsiding rift basin. The relatively free-flowing tholeiitic basaltic lava emanating from rift-system fissures contained, on average, around 65 ppm copper as primary disseminated native metal. In the sub-aerial conditions, sulphur and other easily volatilised components were vaporized instead of forming copper sulphides.

Single eruption lava flows typically consist of: 1) a chilled basal layer, which may be somewhat porous due to gas vesicles; 2) massive lava making up the bulk of the flow, and 3) a highly vesicular flow top, which may be eroded, fractured and weathered.

During subsequent burial, pressure and temperature in the volcanic sequence were increased to approx. 1500 bar and 280° C, respectively. These values are interpreted from the characteristic mineral assemblages, including, e.g., albite, laumontite, prehnite, pumpellyite, analcime and epidote. These minerals indicate low-grade metamorphism. Age determinations indicate that these epigenetic changes in mineral composition took place at least 15 million years after the eruption of the basalts.



Figure 2. Copper crystal (2 cm) showing well developed crystal forms. Quincy mine, Keweenaw, Michigan. The A. E. Seaman Mineral Museum, Michigan Technological University. Photo John A. Jaszczak.

Fluid inclusion study of the minerals has revealed that the fluid phase during alteration of the basalts was a Ca-Na-Cl brine, with total salinities varying between 3 – 20 % (Livnat et al. 1983). Metallic copper dissolves in very hot (up to more than 200° C) chloride brines as Cu(I)-chloride complexes. Copper-bearing solutions were migrating upwards along porous horizons until, during cooling, metallic copper precipitated in void space in vesicles forming copper amygdaloids, in open grain interspaces and in fractures. Metallic copper also replaced some minerals in the host rock and earlier secondary minerals. The most spectacular manifestations of native copper crystallized

as fissure deposits, where copper masses up several tons are found. Void spaces also allowed the crystallization of grains with well-developed crystal faces.

In terms of the total dissolved solids (TDS) and chloride concentration, present-day deep groundwaters within the Portage Lake Volcanics are comparable to those in existence during the formation of the native copper deposit. Lane (1908, 1914) reported total salinities up to 30 %, and chloride concentrations up to 176 g/L. Two dissolved copper analyses were given in those papers: 16 mg/L and less than 8 mg/L for waters having Cl-concentrations 175 g/L and 45 g/L, respectively. These analyses were for stagnant waters from the Quincy mine (level 55) and the Isle Royale mine (level 19), situated near Hancock and Houghton respectively. These values demonstrate the solubility of metallic copper in concentrated chloride brines at the anticipated ambient temperatures in a nuclear waste repository after the decay of the initial temperature spike.

**Relevance:** The Keweenaw native copper deposits demonstrate the stability of metallic copper in an oxidizing environment over a timescale of several million years. Relevant results from the studies of the Keweenaw district concerns the behaviour of metallic copper in concentrated chloride brines and related temperature effects.

**Position(s) in the matrix tables:** Mechanical integrity of barriers=>corrosion=>copper package

**Limitations:** Modern, comprehensive data on groundwater composition and physicochemical characteristics (Eh, pH, T) of deep brines are not available.

**Quantitative information:** These studies provide a crude estimate of metallic copper solubility in low-temperature Cl-rich brine.

**Uncertainties:** Hydrogeochemical data.

**Time-scale:** Geological, hundreds of millions years.

**PA/safety case applications:** Demonstration of copper canister longevity in chloride brines.

**Communication applications:** Demonstration of metallic copper stability in near-surface oxic conditions.

#### **References:**

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**Added value comments:** None

**Potential follow-up work:** None suggested

**Keywords:** near-field, copper, corrosion, saline waters, mines

**Reviewers and dates:** Lasse Ahonen, GTK (April, 2004)