Michigan International Copper Analogue (MICA) II project – recent advances

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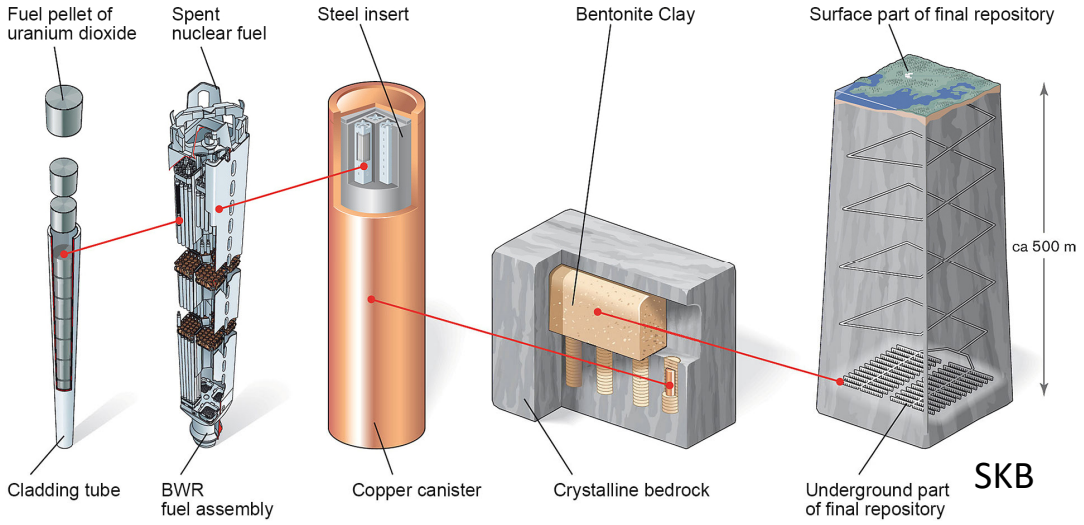
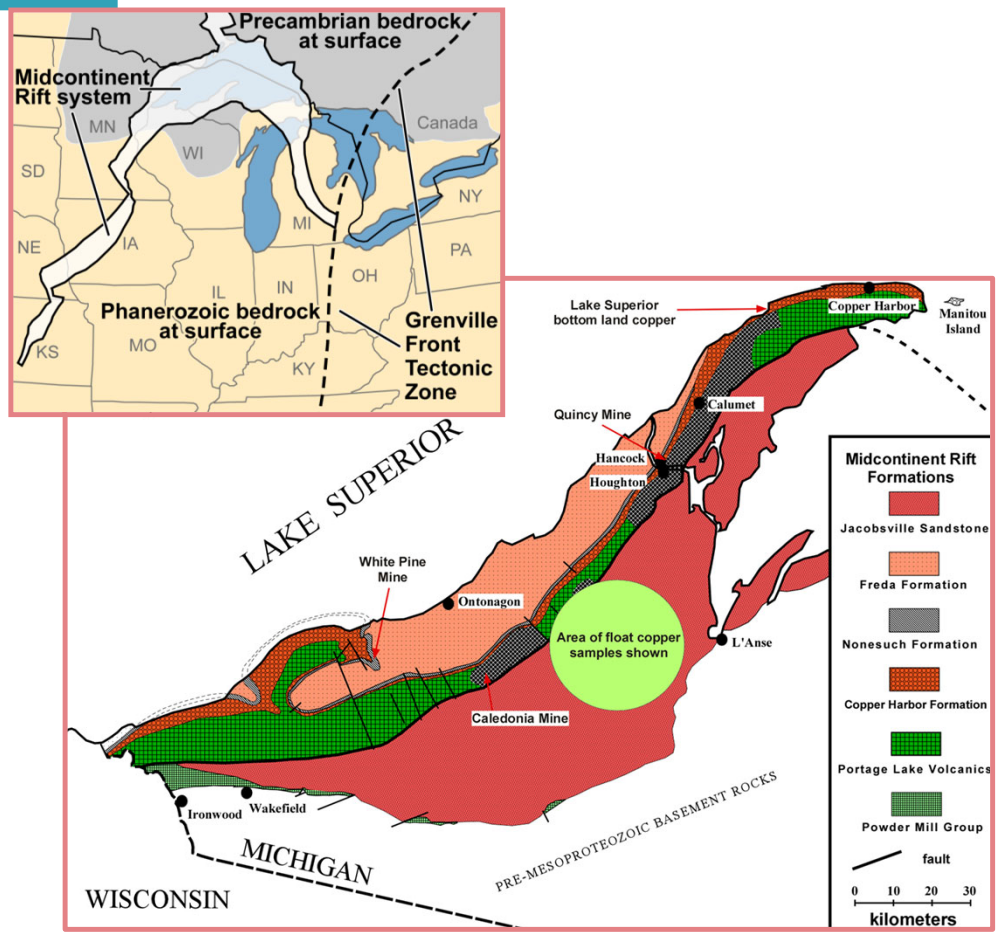
Natural Analogues and Copper

- Copper is a main release barrier of several nuclear waste disposal concepts.
- Copper stability is mainly studied in short-term investigations (months to years).
- Natural and archaeological analogues can complement laboratory studies and provide insights in long-term stability and corrosion issues of copper under real geologic boundary conditions.



Keweenaw Peninsula Copper

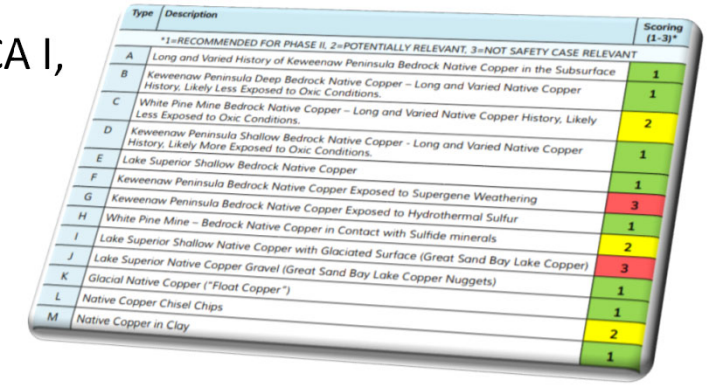


- A Precambrian continent rifted apart 1.1 Ga (Midcontinent Rift system), and volcanic and sedimentary material filled the rift
- Metamorphogenic hydrothermal fluids mineralized native Cu in the pore spaces of the rocks 1.04–1.07 Ga
- Strong erosion ca. 1.0–0.5 Ga
- GW interaction and formation of a supergene minerals
- Buried by Phanerozoic sediments ca. 500–175 Ma
- Quaternary glacial processes exposed the copper deposits again
- 7 000 years ago, humans first exploited copper in Keweenaw Peninsula
- Modern copper mining since 1845–1968
- Post-mining processes

Project Background

- The Michigan International Copper Analogue (MICA) project focuses on the stability of native copper in the world's largest native copper dominated deposits of the Keweenaw Peninsula
- The MICA I Project, reported in 2023, assessed copper stability and proposed a classification of analogue types

- In MICA I, total of 13 analogue types were described and ranked.
- MICA II targets three analogue types, selected based on MICA I, for repository applications:
    1. Bedrock Copper
    2. Copper in Clay
    3. Copper and Copper Sulfides
- The aim is to build a dataset supporting repository safety cases and stakeholder communication on long-term evolution.
- MICA II is a collaboration between the Swedish Nuclear Fuel and Waste Management Co, the Korea Atomic Energy Research Institute, and the Geological Survey of Finland.



Type	Description	Scoring (1-3)*
	*1=RECOMMENDED FOR PHASE II, 2=POTENTIALLY RELEVANT, 3=NOT SAFETY CASE RELEVANT	
A	Long and Varied History of Keweenaw Peninsula Bedrock Native Copper in the Subsurface	1
B	Keweenaw Peninsula Deep Bedrock Native Copper – Long and Varied Native Copper History, Likely Less Exposed to Oxic Conditions.	1
C	White Pine Mine Bedrock Native Copper – Long and Varied Native Copper History, Likely Less Exposed to Oxic Conditions.	2
D	Keweenaw Peninsula Shallow Bedrock Native Copper - Long and Varied Native Copper History, Likely More Exposed to Oxic Conditions.	1
E	Lake Superior Shallow Bedrock Native Copper	1
F	Keweenaw Peninsula Bedrock Native Copper Exposed to Supergene Weathering	3
G	Keweenaw Peninsula Bedrock Native Copper Exposed to Hydrothermal Sulfur	1
H	White Pine Mine – Bedrock Native Copper in Contact with Sulfide minerals	2
I	Lake Superior Shallow Native Copper with Glaciated Surface (Great Sand Bay Lake Copper)	3
J	Lake Superior Native Copper Gravel (Great Sand Bay Lake Copper Nuggets)	1
K	Glacial Native Copper ("Float Copper")	1
L	Native Copper Chisel Chips	2
M	Native Copper in Clay	1

Analogue Types

General copper stability

Stability of the repository system

Stability when the system is disturbed

Bedrock Copper

- Sampling from museum collections, Quincy Mine
- Copper in basaltic lavas
- Producing data on less altered native copper at repository relevant depths
- Collecting detailed mineralogical and chemical data and descriptions of the host rock conditions
- Assessing the similarities to the copper in the repository system

→ Analogue for normal evolution, baseline for other analogue types

Copper in Clay

- Native copper in fault filling materials, e.g., in Hancock Fault in Quincy mine
- Assessing the relevance for the repository system
  - Copper composition and alteration, properties of the clay?
  - Structural framework, groundwater circulation?

→ Estimation of potential to use the site for waste package + buffer performance analogue, normal or disturbance evolution?

→ First description of the occurrence to science with enough details for safety case use!

Copper and Copper Sulfide Systems

- Native copper crosscut by later sulfide bearing hydrothermal fluids
- Assessing the corrosion processes occurring in various conditions where native copper and copper sulfide minerals co-exist
- Corrosion mechanisms and products are studied
- Comparisons to the other sites

→ Analogue for copper stability under sulfide attack

→ New information on the corrosion minerals

Field Work 2025

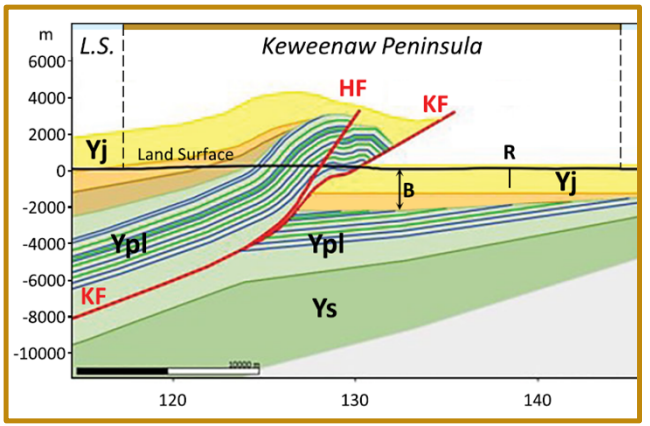
- In May 2025, 61 samples were collected from six mines, waste piles, and collections of the A.E. Seaman Mineral Museum, Houghton.
- Structural observations were made to document geological context.
- Aim was to meet needs of planned analyses.

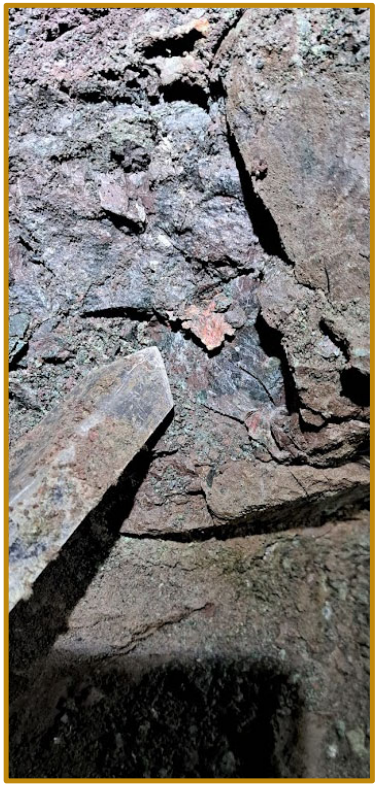
Sites

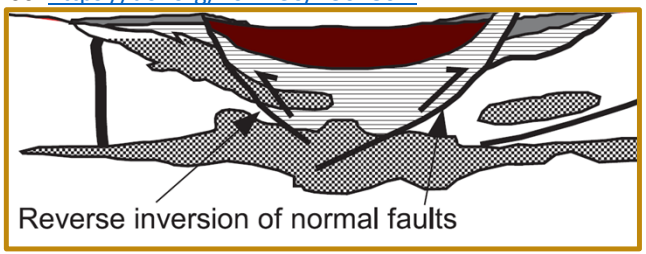

Copper Harb
41
Delaware
Calumet
Lake Linden
Quincy
Houghton
Atlantic Mine
Seaman Museum
Chassell
Champion
Ontonagon
41
Big Bay
White Pine
Adventure
L'Anse
Bergland

Hancock Fault – Copper in Clay

- Part of the larger Keweenaw Fault System
- Inversion Model: the fault system was originally formed as a normal fault during rift extension (graben formation), and later reactivated in reverse during compressional events.
- New Model (DeGraff & Carter, 2023): Formed directly as a primary thrust fault during compression (no extensional history).



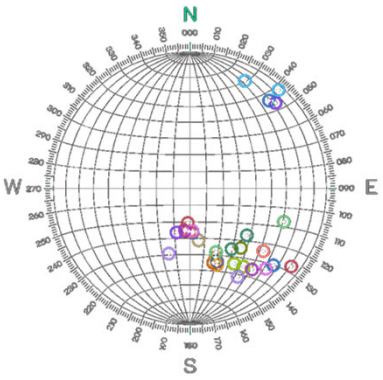


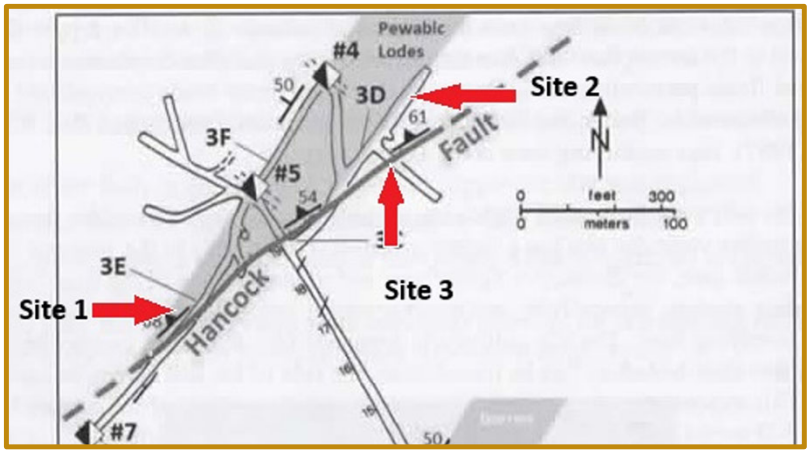


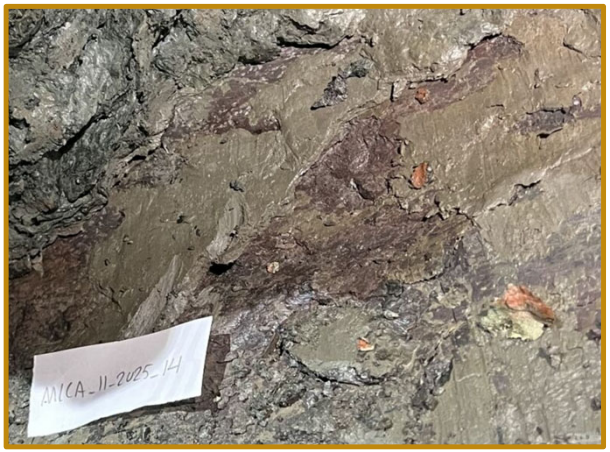
DeGraff, J.M., Carter, B.T., 2023. Detached structural model of the Keweenaw fault system, Lake Superior region, North America: Implications for its origin and relationship to the Midcontinent Rift System. GSA Bulletin 135, 449–466. https://doi.org/10.1130/B36186.1

Hancock Fault – Clay Samples

- At Quincy, native Cu mineralization is mainly hosted by lava flows of the Portage Lake Volcanics and locally controlled by fracturing related to NW dipping Hancock fault.
- Extensive fault couge sampling at three locations at the depth of 100 m.
- 8 samples were selected for preparing thin sections.
- The samples were freeze-dried, vacuum epoxy impregnated. Cured samples were sawed and thin sections are now prepared in the laboratory of Geohouse, Turku.

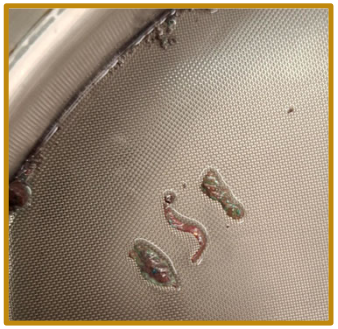






Further Analytical Work

	Copper in Clay	Bedrock Copper & Sulphide Systems
XCT	3D imaging of the internal structure of the fault material Identification of Cu	Setting of the copper in the sample Aid in thin section preparation
SEM and EDS	2D imaging, mineral identification	Mineral identifications, including any corrosion products
FE-EPMA	Major and minor element contents of copper and clay	Copper purity assessment Trace element mapping in corrosion products
Petrophysics		Similarity of conditions in intact rock and bentonite buffers
XRD	Identify clay species	
K/Ar	Defining the age of illites /potassiun phases (K-feld)	

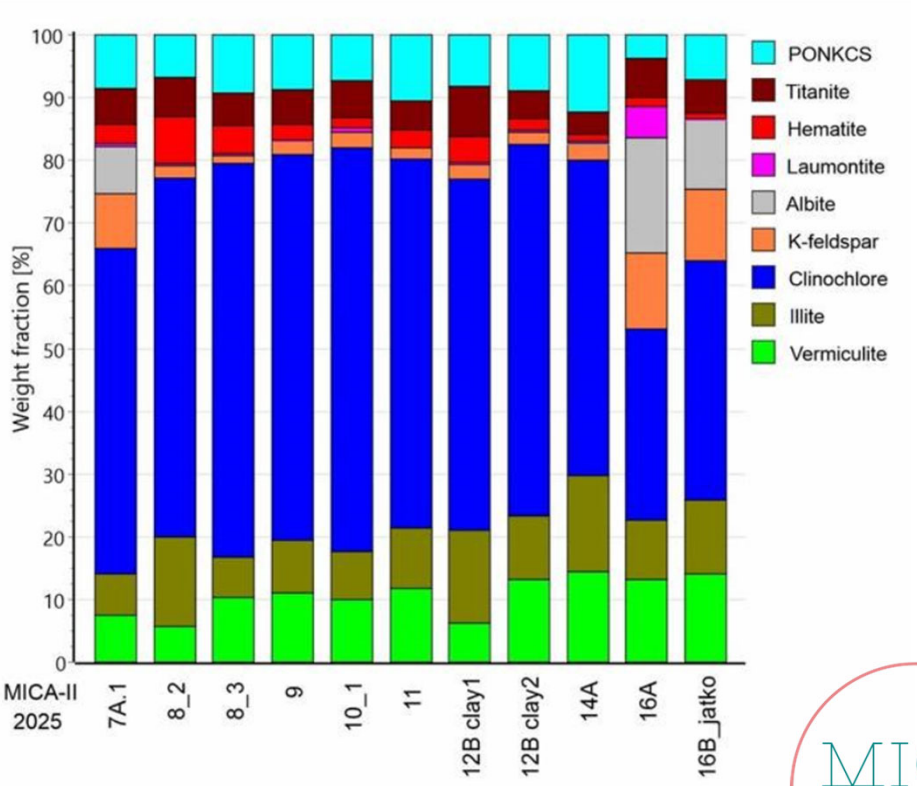


→ **Understanding the copper properties, surrounding geological conditions, significant processes, time frames and their uncertainties**

→ **Shifting from a descriptive curiosity to process-based tools that can inform safety cases**

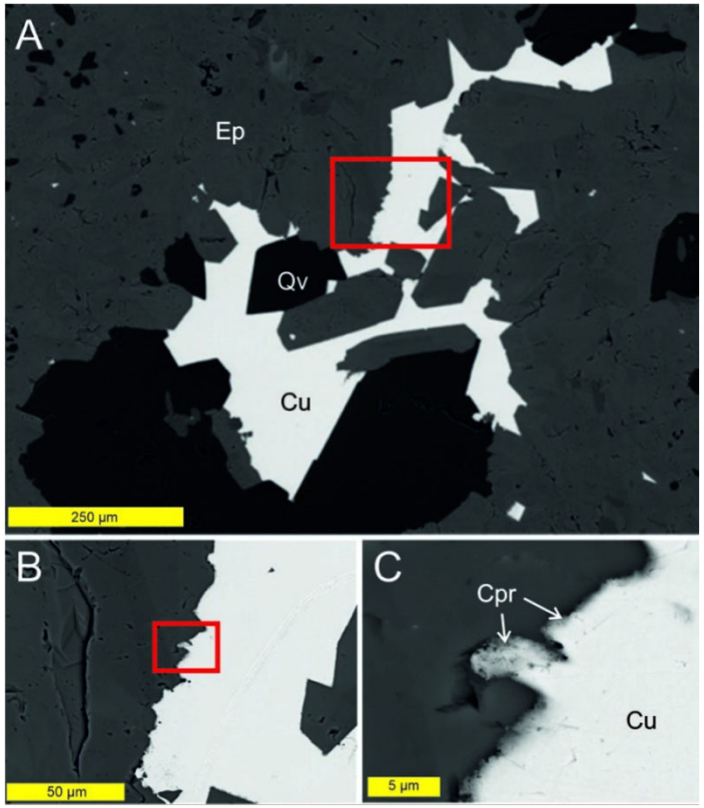
Some initial XRD results from the clay seams (Quincy)

- Predominantly composed of clays resembling chlorite, vermiculite/smectite and potentially also corrensite-like mixed-layer clays
- Analogue for clay, but not directly bentonite (“not as good as buffer”)
- Massive clays
- **No copper bearing alteration products observed** (except one minor malachite), **native copper nuggets** were extracted from the powders before analysis



PONKCS = Partial Or No Known Crystal Structure (allows modelling of poorly crystalline phases, e.g. smectites)

SEM results – baseline vs. copper in clay



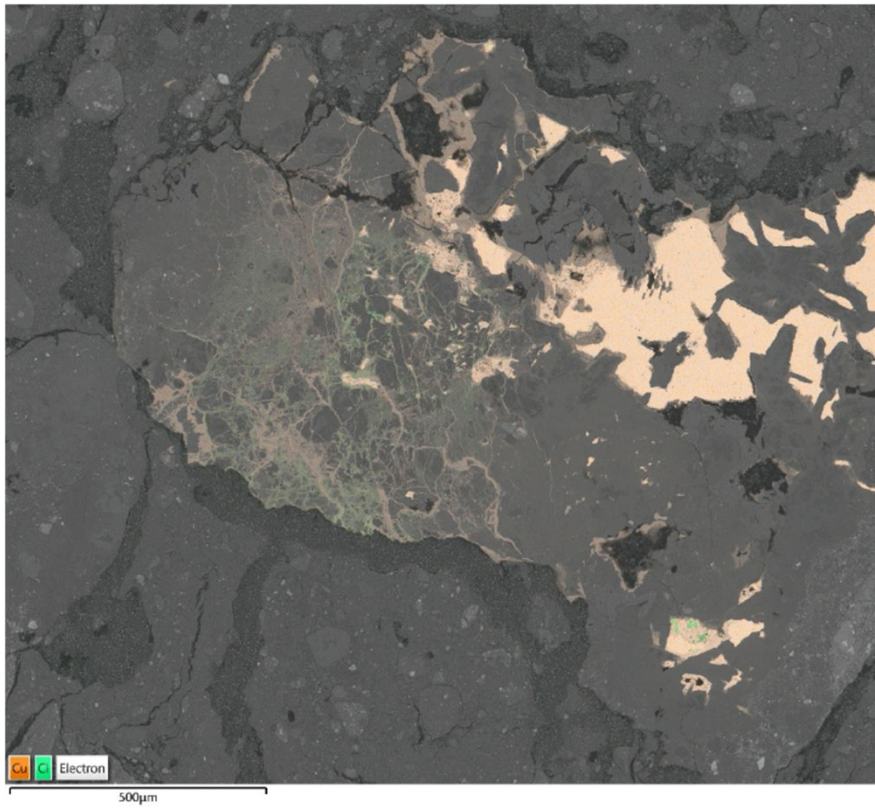
← In baseline samples only minor alteration observed in some edges of the native copper (Cu-oxide, cuprite)

→ Native copper in clay occurs in clastic material and as separate nuggets

→ Minor alteration observed (oxides, carbonate, chlorites)

→ Mobility of copper is seen in clasts (predates fault gouge formation)

→ No copper alteration products in the clay phases



Ep=epidote, Cu= native copper, Cpr, Cuprite, Qv= Quartz

Conclusions

- Currently the team is finalising the analytical programme
- Overall, it seems that the minor copper alterations seen are ancient (hundreds of millions years) and not much further copper alteration has occurred in the fault (hypothesis is that copper is older than fault)
- Suitable epoxy thin sectioning method has been developed for these challenging clay-copper samples
- Final report in the Autumn 2026
- MICA III under planning, potential for:
  - Microbial analyses in copper-clay environments
  - Drilling samples from tunnels to obtain clean samples and complete cross-sections
  - Geochronology from additional phases…apatite etc.
  - Adding samples from other locations (comparison to float coppers and known Finnish native coppers)

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