Secondary Minerals in Basaltic Caves: Analog for Mars Surface and Subsurface Mineralogy

The purpose of this study
1. Examine the alteration products and processes of terrestrial lava caves
2. Determine the mechanisms by which Mars-like alteration products, including sulfates, minerals, silica, and hematite, form in an Fe-rich basaltic cave environment on Earth.
3. Suggest how these mechanisms may (or may not) be analogous to Martian processes.

Our sites
- Lava Beds National Monument, California
- Dormant lava system in 30-km south of lava flows (some younger)
- Kula Kai Caverns, Big Island, Hawaii (part of the Kapuka Kaua lava tube system in <2000 year old lava flows from Mauna Loa)
- Other sites have calcite, silica in some form, and hematite.

Our Lava Tubes
- The lava tubes of CoM and Lava Beds range from small to extensive; Kula Kai is extensive. CoM has sulfite mounds [2]. CoM and Kula Kai have Na- and Ca-sulfite coatings, and all three sites have calcite, silica in some form, and hematite.

Sulfate mounds and crusts
- Secondary sulfate minerals at CoM are concentrated in powdery or snow-like mounds on the cave floors. Thick calcite crusts of macrinite occur near cave entrances at both CoM and Kula Kai. Fe-carbonates and sulfates dominate, though jarosite was identified in a ceiling coating of one CoM cave [3].

Formation mechanisms
- Shortly after cave formation high-T (both dry and hydrothermal) processes drive oxidation of basalts to FeO⁻² bearing minerals into hematite, and less soluble secondary minerals precipitate [4-5].
- Gypsum and some other sulfates can form at high and intermediate T. As the temperature drops, less soluble high-T minerals are destroyed and replaced by lower-T, more soluble minerals [6].
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- Once the cave is cool, calcite, gypsum, Na-sulfate, and carbonates, and amorphous silica can precipitate from seeping water or sublimating ice [6-12].
- Some minerals, e.g. thorinite and mirabilite, fluctuate seasonally; some, e.g. hematite, remain from the early high-T processes. Figure from [6].

References

Lava Caves in the Solar System
- Recently observed on the Moon and Mars [7-9].
  - Potential astrobiological target: provide protection for organisms, biosignatures from UV radiation and cosmic particles [10].
  - In acid places on Earth, preserve soluble Mars-analogous secondary minerals e.g. Na- and Fe-sulfates.

Sulfates, hematite, and silica on Mars
- High-Fe basalts and related alteration products abundant on Martian surface.
- Detection of minerals such as sulfates (e.g. jarosite, gypsum), hematite, and silica at the MER landing sites and more broadly on Mars has often been interpreted as evidence of ancient Martian aqueous activity [e.g., 11,12,13,14,15].
- The nature of the deposits, and comparisons to terrestrial analog environments, can help determine whether they formed by evaporitic, hydrothermal, groundwater, or other conditions.

Comparison to Mars
- CoM basalts have similar Fe contents to Mars basalts.
- Kula Kai and Lava Beds have lower Fe but are closer to Mars basalts in T, K, and T.
- Geochemical pathways of alteration are dependent on the starting composition fine particles, which may be analogous to Mars.
- The caves preserve Mars-relevant secondary minerals formed on basaltic substrate.
- Jarosite, abundant at the Opportunity landing site, is present in CoM caves.
- Hematite in the lava caves formed by alteration of the basaltic substrate, presumably at high temperatures.
- Morabito Planum hematite is most often interpreted as a low-T phase [e.g. 18], though a hydrothermal origin has been suggested [e.g. 20].

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