EXTENDED, HIGH-TEMPERATURE COOLING OF LAVA TUBE INTERIORS: ANALOG FOR VENUS.

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Introduction: Venus has a volcanically active surface, with evidence for recent or even current volcanic activity. Analyses of surface rocks by Venera landers suggests a basaltic composition, though silicic materials have been inferred for some regions, based in part on differences in emissivity. ESA's Venus Express (2006-2014) had a spectrometer [1] that analyzed emissivity in the near infrared (around 1 micron), distinguishing between low emissivity and high emissivity areas, which could indicate basaltic compositions in the lowlands and more silica-rich compositions in highland areas, respectively, and also suggest that some tesserae are more silica-rich than the surrounding likely basaltic plains [2]. However, these interpretations are complicated by surface alteration, since the oxidation of basaltic surfaces at high temperatures (a likely process, given the oxidizing conditions on the surface of Venus) could form a veneer of hematite, which has a lower emissivity than the original basalt [3]. In particular, this surface coating of hematite could mask the presence of olivine from orbital sensors [3].

The surface of Venus is much hotter (~464°C) and atmospheric pressure is much higher (90 bars) than Earth. Minerals that are abundant on Earth such as carbonates and hydrous minerals would be unstable at such elevated temperatures, and rocks such as basalts exposed to such conditions would weather differently than they do on Earth. Thus, what we observe at the surface of Venus using orbital spectroscopy could be quite different from the bulk composition, because of interactions between rock and atmosphere over time.

Filiberto et al. (2020) [3] recently published an experimental study, in which they experimentally weathered olivine crystals at high temperatures to simulate Venus surface conditions. These artificially weathered olivines were spectroscopically distinct from the original, as the mineral hematite formed a thin surface coating. This thin coat would effectively mask the presence of olivine from remote sensing spectroscopic tools, and they argue that the detection of olivine at all on the surface of Venus could mean that there are very young volcanic deposits that haven't yet completely undergone this coating process.

Terrestrial lava tubes: Finding a natural environment on Earth where basalts cool slowly in contact with elevated temperatures is tricky, given the much lower temperatures prevalent on the Earth's surface. However, the interior of a newly-formed lava tube could provide such an environment. The surface of a lava flow erupted on Earth's surface is immediately exposed to low temperature environment, limiting the time over which it could oxidize at high temperatures [4]. Basaltic lava tubes form where the surface of a lava flow crusts over, insulating the flow of lava beneath the surface. As the ongoing lava flow excavates a deeper channel over time (and as the level of the lava rises and lowers due to pulses of eruption), the upper parts of the lava tube will be filled with super-heated air and volcanic gas (e.g., [5]). Multiple generations of lava flows can flow through the tube, heating the interior. Even as the lava in the tube eventually stops flowing and solidifies, the air within the tube can remain insulated and hot for months to years. Lava on the ceilings often solidifies as "drip" features, similar in appearance to stalactites. For those to form, conditions in the tube need to be hot enough for the basalt to be at least partially melted. Minerals that crystallize within the vesicles (trapped air bubbles) in some lava stalactites probably formed from heated vapors at around 1100°C [5], and these surfaces continue to interact with the hot interior environment of the lava tube as it cools. Forti (2005) [6] describes six stages of secondary mineral formation upon cooling of a lava tube, only the first (high followed by low-temperature degassing) would be relevant under Venus temperature conditions.

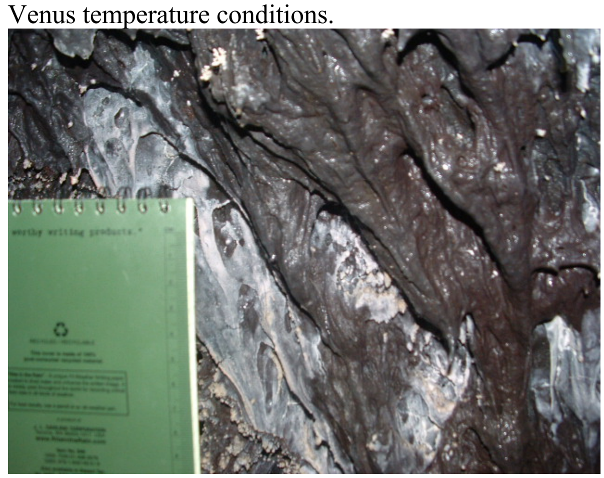

Fig 1) Lava tube interior, Arco Tunnel, Blue Dragon Flow. Specular coating is hematite-rich, thin white coat is amorphous silica.

Craters of the Moon National Monument (COM) and methods: The ~60 basaltic lava flows at COM were emplaced between 15,000 and 2100 years ago [7]. Lava tubes are common, especially in the Blue Dragon Flows (e.g. [8]). We observed a specular "sheen" on interior surfaces within lava tubes in the Blue Dragon flow (Wilderness Caves and Cave Trail areas) and collected pieces of fallen lava stalactites with clean surfaces, and less altered basalt from the same flow.

Methods: We acquired a powder of the surface layer using a dental drill and collecting the tailings, and also powdered a less-altered bulk basalt sample. Both powders were analyzed by powder X-ray Diffraction (XRD) using a Bruker D8 Focus (mineral assemblage) and fused and analyzed by X-ray Fluorescence (XRF) using a Bruker S4 Pioneer (major elements). We mounted and polished chips of the lava tube interior samples for Scanning Electron Microscopy (SEM) analysis using a Hitachi S-4800 equipped with a Bruker Energy Dispersive Spectrometer (EDS).

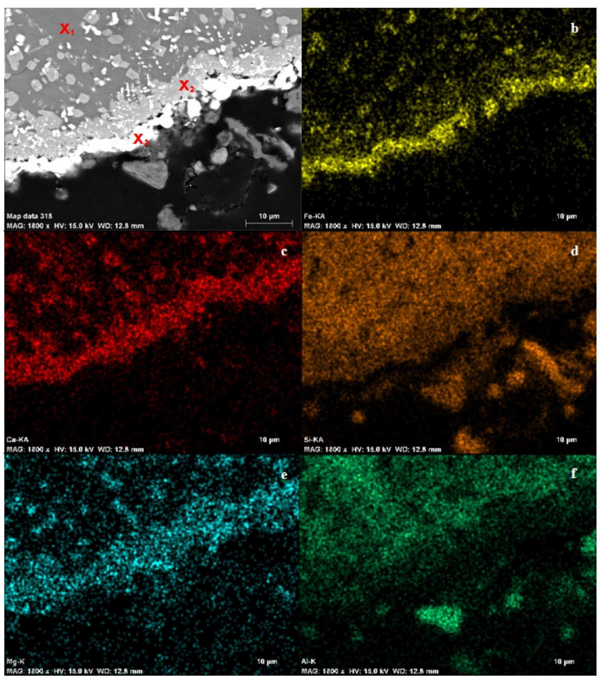

Figure 2) Backscattered electron (BSE) image of a lava tube chip and element maps for Fe (yellow), Ca (red), Si (orange), Mg (blue), and Al (green). The hematite-rich surface layer is clearly visible as the bright layer in BSE and in the Fe abundance map (also Si-poor). Directly beneath the surface is a clinopyroxene-rich layer of intermediate brightness in BSE (with elevated Ca and Mg). The interior of the sample consists of basaltic glass with phenocrysts, with higher Si and Al.

Results: These results show that a hematite-rich layer developed at the surface of the basalt as it cooled within the lava tube, which would have been exposed to high temperatures for an extended period as the lava tube cooled. In this environment, olivine was oxidized and a thin layer of hematite formed at the surface. The pattern of element distribution show in Figure 2 shows a redistribution of cations during cooling.

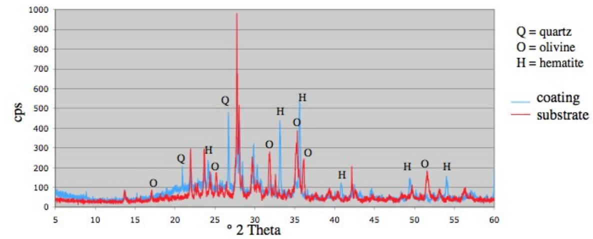

Figure 3) XRD plots for the surface coating (blue) and a less altered sample of the Blue Dragon Flow (red), with quartz, olivine, and hematite peaks labeled. The basalt sample did not contain detectable hematite, while this phase was abundant in the surface sample. In contrast, olivine was abundant in the basalt but not in the coating. Figure from [9].

Discussion: This Fe-rich layer likely formed due to cation migration at elevated temperatures, following solidification, similar to in [4]. These trends are similar to previously published experiments conducted to model basalt [10] and olivine [3] weathering at Venus-like temperatures. In those experiments, a thin coating of hematite formed and darkened the surface of olivine, weakening the 1 micron absorption feature of olivine over time (which would make olivine more difficult to detect from orbital spectra).

We propose that the interiors of basaltic lava tubes, which provide an environment in which lava remains in a high-temperature surface environment for days, weeks, or months following solidification, could serve as a useful analog for weathering under Venus surface temperatures, with the formation of hematite surface coatings as an example. Future work could include Near-Infrared spectroscopic analysis of lava tube basalt surfaces, and a comparison between more quickly cooled lava surfaces (surface lava flows) and lava tubes from the same flows, to assess the effect that the length of time exposed to high temperatures after solidifying has on the surface mineralogy.

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