Investigation of Alteration Conditions within Volcanic Cave Systems: Analogue for Venus Surface Geology

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Abstract

High surface temperatures and a thick atmosphere, rich in carbon dioxide severely limit orbital spectroscopic and in-situ research of geologic processes on Venus, including its mineralogy. Remote reflectance spectroscopy is limited to observations in only three near-infrared windows. These measurements are capable of measuring relative ferrous iron abundance, but variations in measurements could result from different causes. Laboratory experiments and modeling have helped Venus researchers interpret spectroscopic readings of the planet's surface. Experiments and models indicate surface-atmosphere interactions alter basaltic rock surfaces to produce secondary minerals like hematite and anhydrite, which may affect spectroscopic readings. Using lava tubes as an analogue for the surface mineralogy of Venus may also prove informative. Lava tubes are geologic landforms that are made in high-temperature, insulated environments and are observed to contain minerals predicted to be on Venus. Tholeiitic basalt samples were collected from the interiors of lava tubes and preliminary data from X-ray diffraction and visible-near infrared spectroscopy indicate the basalt samples had altered under high-temperature conditions near or above that observed on Venus.

Introduction

Research of the surface geology of Venus through remote imagery and in-situ analysis is limited by obstructing atmospheric conditions and temperature. Venus' atmosphere is composed of ~96.5% CO2 (carbon dioxide) with trace amounts of SO2 (sulfur dioxide) and lesser gas species (Zolotov, 2018). The average atmospheric pressure and temperature is ~95.6 bars and 467°C (Seiff et al., 1985; Zolotov, 2018). In addition to inhospitable conditions for scientific instruments, a general lack of exploration means much is still unknown about the planet. Compositional knowledge of Venus' surface geology is largely limited to three XRF (X-Ray fluorescence) analysis and several gamma-ray spectroscopy measurements from the 1970s and 80s by USSR landers (e.g.- Dyar et al., 2021 and references therein). The dense CO2 atmosphere limits orbital remote spectroscopy to observations in only a few NIR windows (1.02, 1.10, and 1.18 µm) (Gilmore et al., 2017). Venus Express (2006-2014) measured Venus' surface emissivity at 1.02 µm, which is a characteristic wavelength for ferrous iron content. High emissivity measured at 1.02 µm indicates higher ferrous iron content, and a lower emissivity indicates less ferrous (or more oxidized) iron (Gilmore et al., 2017).

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Both in-situ data and orbital spectroscopy suggest the surface geology to be composed of sub-alkaline basalts. Regions of Venus emitting higher emissivity are interpreted to be younger, unweathered basaltic flows (Smrekar et al., 2010). Whereas regions of lower emissivity could indicate two options: a weathered and therefore more oxidized basalt surface, or a more silicic composition (Gilmore et al., 2017). Gamma ray spectroscopy of some regions with lower emissivity, like the tesserae, suggest that compositions like rhyolite or granite are present on the surface (Vinogradov et al., 1973; Dyar et al., 2021). Verifying these results could have significant implications for past water and tectonic activity of the planet, two important factors for habitability (Foley, 2015). A better understanding of Venus' surface spectroscopy also provides insight for current geologic processes. Laboratory experiments weathering basalts under Venus-like conditions reveal that secondary minerals, such as iron oxides, form over the surface on a timescale of weeks to months (e.g.- Filiberto et al., 2020; Cutler et al., 2020; Santos et al., 2023). Therefor the presence of unweathered basalt would indicate recent to active volcanism on Venus.

This research project aims to better understand how surface weathering under Venus-like conditions can alter a rock's composition and its emissivity. Basaltic rock samples were collected from the interior of lava tube systems as a potential analogue for Venus surface geology. These volcanically formed caves may host a high-temperature alteration environment similar to Venus. Prior research performed by Ruffini (2011) reveals that surfaces of some lava tubes exhibit a metallic veneer, and further SEM (Scanning Electron Microscopy) analysis shows evidence for cation migration, which is indicative of a high temperature oxidation environment (Minitti et al., 2005). This research further examines the origin of these features.

The objective of this project is to investigate the alteration conditions of lava tubes. Analysis will be performed on secondary minerals present and their alteration mechanisms. Alteration mechanisms and mineralogy will be compared to those on the surface of Venus. This would be done by characterizing the mineralogy of the metallic luster surfaces of samples collected from lava tube walls and the underlying sample interiors, characterizing the bulk elemental composition of sample exteriors and interiors, analyzing spectral signatures using VNIR (Visible-Near Infrared) spectroscopy, and studying textures and element distributions using SEM analysis of sample cross-sections and surfaces.

Geologic Background

In November 2022, we traveled to the Big Island of Hawai'i to collect samples from several volcanically formed conduits, known as lava tubes. The Big Island and the rest of the Hawaiian Islands are all products created by hot spot volcanism. This hot spot located underneath the Pacific Plate is a concentration of hotter than typical rock within the Earth's mantle that generates a steady supply of magma that erupts onto the Earth's surface (Hazlett and Hyndman, 1996). This style of volcanism produces tholeiitic basalts, a type of subalkaline basalt (Yang et al., 2023). Samples were collected from lava tube systems from both Mauna Loa and Kilauea volcanoes. These shield volcanoes are the most active of the island, as they are the youngest and still in their shield building stage (Eaton and Murata, 1960).

The two main lava tube systems we sampled from are Kipuka Kanohina and Puʻuʻōʻō (Figure 1). The Kipuka Kanohina lava tube system is sourced from the Mauna Loa Volcano. Kipuka Kanohina formed ~800 years ago off the southwest rift zone (Lockwood and Lipman, 1987). The Puʻuʻōʻō lava tube system began cooling ~5 years ago and formed near the end of the thirty year eruption of the cinder-and-spatter cone, sourced from Kilauea Volcano (Heliker and Mattox, 2003; Neal et al., 2019).

Lava tubes are of particular interest because of their distinct minerogenic environment. These geologic features are a common landform created by effusive lava flows. These roofed conduits form when the outer layer of a lava flow, exposed to the cooler air, solidifies and covers the still-flowing interior. Thermal erosion and changing pulses in lava flows permit superheated gas to fill the upper voids of the tube. These conditions provide for a wellinsulated environment. Research has shown that flows through lava tubes only decrease in temperature by ~0.5-1°C/km (e.g. Helz et al., 2003; Thornber, 2001). Temperatures within lava tubes also remain elevated for extended periods, ranging from months to years after the last flow event (e.g. Porter, 2000). During the active and cooling stages of lava tubes, a wide variety of secondary minerals are formed including prominent iron oxide and sulfate minerals that experiments indicate are present on the surface of Venus (Sawlowicz, 2020 and references therein).

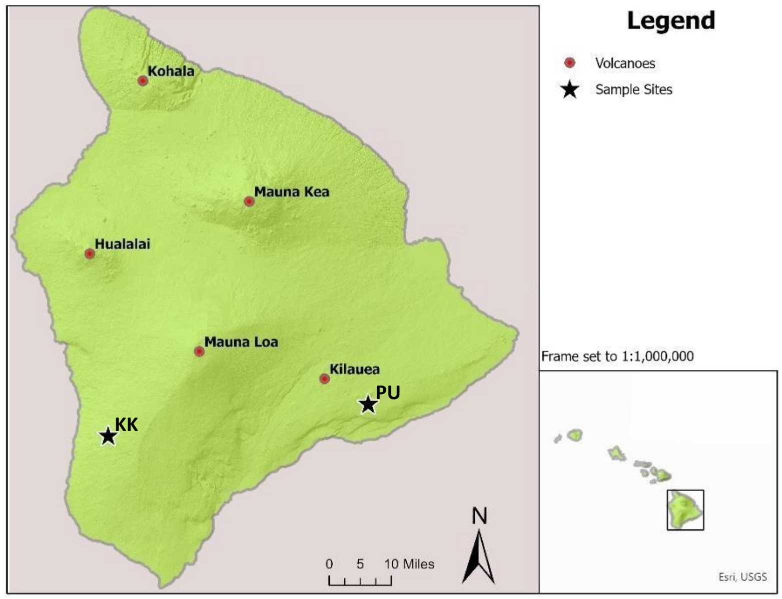


Figure 1 Map of the Big Island of Hawai'i. Red dots represent the approximate crater locations of each respective volcano. Black stars indicate the general area of where samples were collected. KK stands for the Kipuka Kanohina cave system and PU stands for the Pu'u'ō'ō cave system. Map data and features collected from ESRI, USGS.

Methods

When collecting samples in the lava tubes, great care was used to minimize any damage. Samples collected were chosen from fallen ceiling and wall fragments. Targeted samples exhibited a smooth, metallic veneer coating the outer surface. Several samples additionally contained yellow and white secondary deposits. Two substrate samples were collected from outside the Kipuka Kanohina and Puʻuʻōʻō lava tube systems. These samples are assumed to be from the same flow that formed each respective tube. Preliminary data for four samples from the 1843 Mauna Loa flow were collected at the University of Hawai'i- Hilo, using their SEM

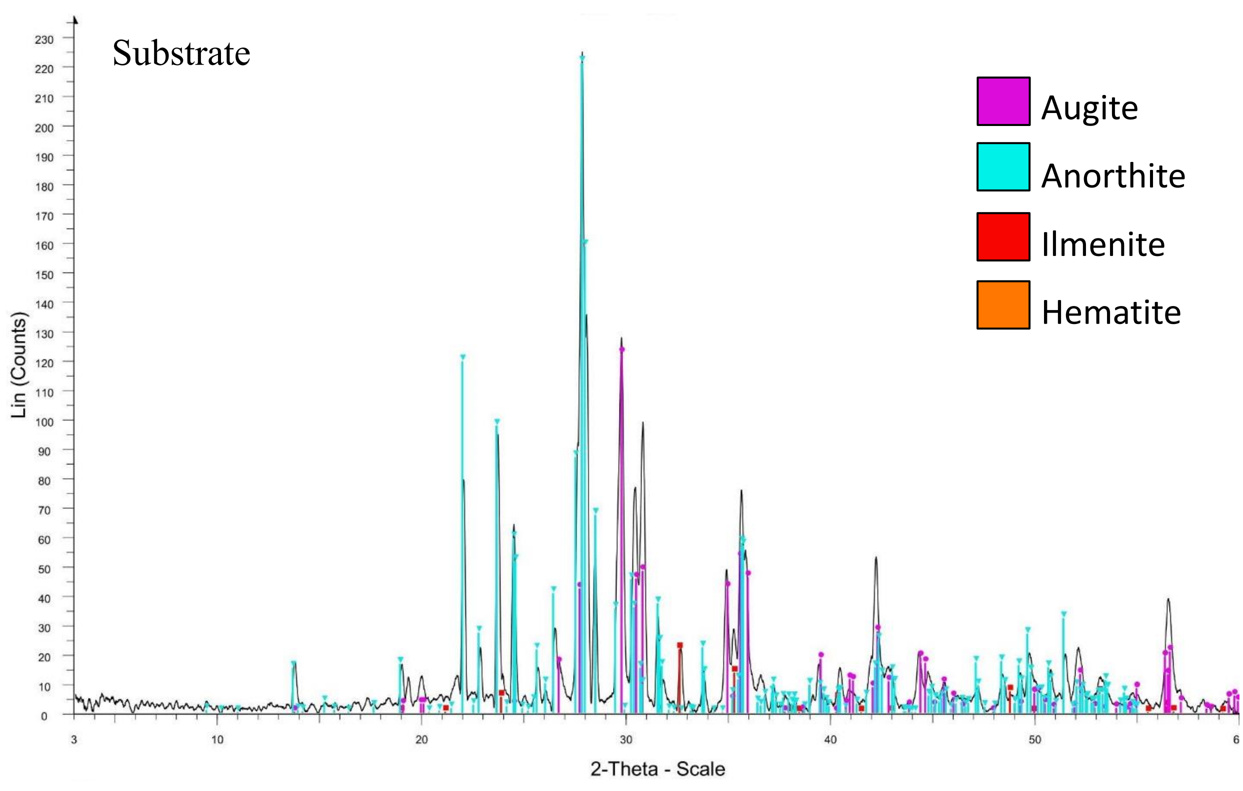
(Scanning Electron Microscope). Samples from Kipuka Kanohina and Pu‘u‘ō‘ō were bagged and brought back to the University of Wisconsin- Milwaukee for further laboratory analysis.

Three different types of samples were prepared for analysis. The first is the substrate samples. The second includes the surface veneers of each lava tube sample. Surface samples were collected by skimming the veneer off using a power drill with a tungsten carbide bur attachment. The third type of sample includes the “interior” of the lava tube samples, which are subsamples of the same sample from the lava tube beneath the veneer. Interior samples were separated and collected using a rock saw.

XRD (X-Ray Diffraction) analysis was conducted to determine the mineral assemblages of sample surfaces and interiors. Surface and interior samples were refined and powdered using a mortar and pestle to achieve a fine enough grain size for the X-ray diffractometer. Each powdered sample was mounted as a random powder and analyzed using a Bruker D2 Phaser X-Ray Diffractometer (3-60° 2-Theta, .01s/step, Cu tube (1.54184 Å) with 30kV, 10mA, LYNXEYE_XE_T (1D) detector). The patterns were interpreted using Bruker’s EVA software and minerals were identified by comparison against the ICDD PDF-2 database. In addition, 1-2cm cuts of sample surfaces were sent to University of Colorado- Boulder for VNIR (Visible-Near Infrared) spectroscopy. Spectral signatures of samples were evaluated for absorption features characteristic of ferric iron and water content.

Results

X-ray diffraction Minerals identified in the KK substrate include anorthite, augite, ilmenite, and hematite. The KK lava tube surface samples contain magnesioferrite, cristobalite, and tridymite in addition to the minerals found in the substrate. Typically interior samples of KK shared the same mineralogy as the surface samples, but in smaller concentrations (Figure 2).



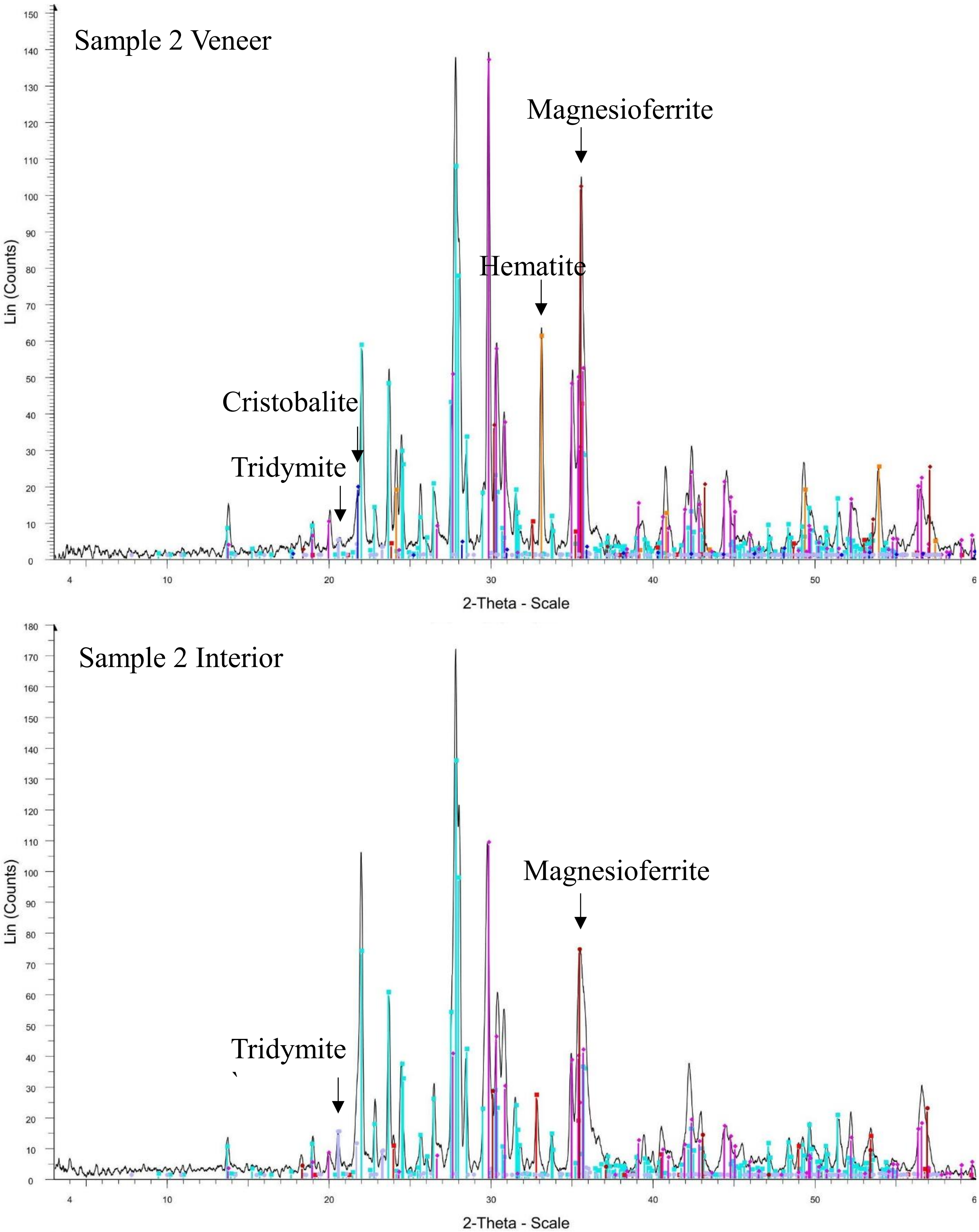


Figure 2 X-ray diffraction patterns of samples from Kipuka Kanohina. The substrate sample is assumed to be the original mineral composition of the lava flow. Minerals of the substrate include: augite (purple), anorthite (cyan), ilmenite (red), and hematite (orange). The veneer and interior of sample two reveal alteration minerals that formed within the lava tube. Each arrow points at the major peak characterizing the respective mineral.

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The PU substrate sample is composed of anorthite, augite, ilmenite, and hematite. Surface samples of the PU lava tube contain magnesioferrite, cristobalite, tridymite, and occasionally gypsum. Interior samples did not contain gypsum, but the other minerals remained present.

Visible-near infrared spectroscopy Wavelength spectra of all KK and PU samples have absorption features around 870 nm, indicating the presence of ferric iron (Figure 3). Sample PU_22_07 is the only sample with an absorption feature at 1400 nm, indicating OH bonds present. A majority of the samples have an absorption feature at 1900 nm, characteristic water molecules

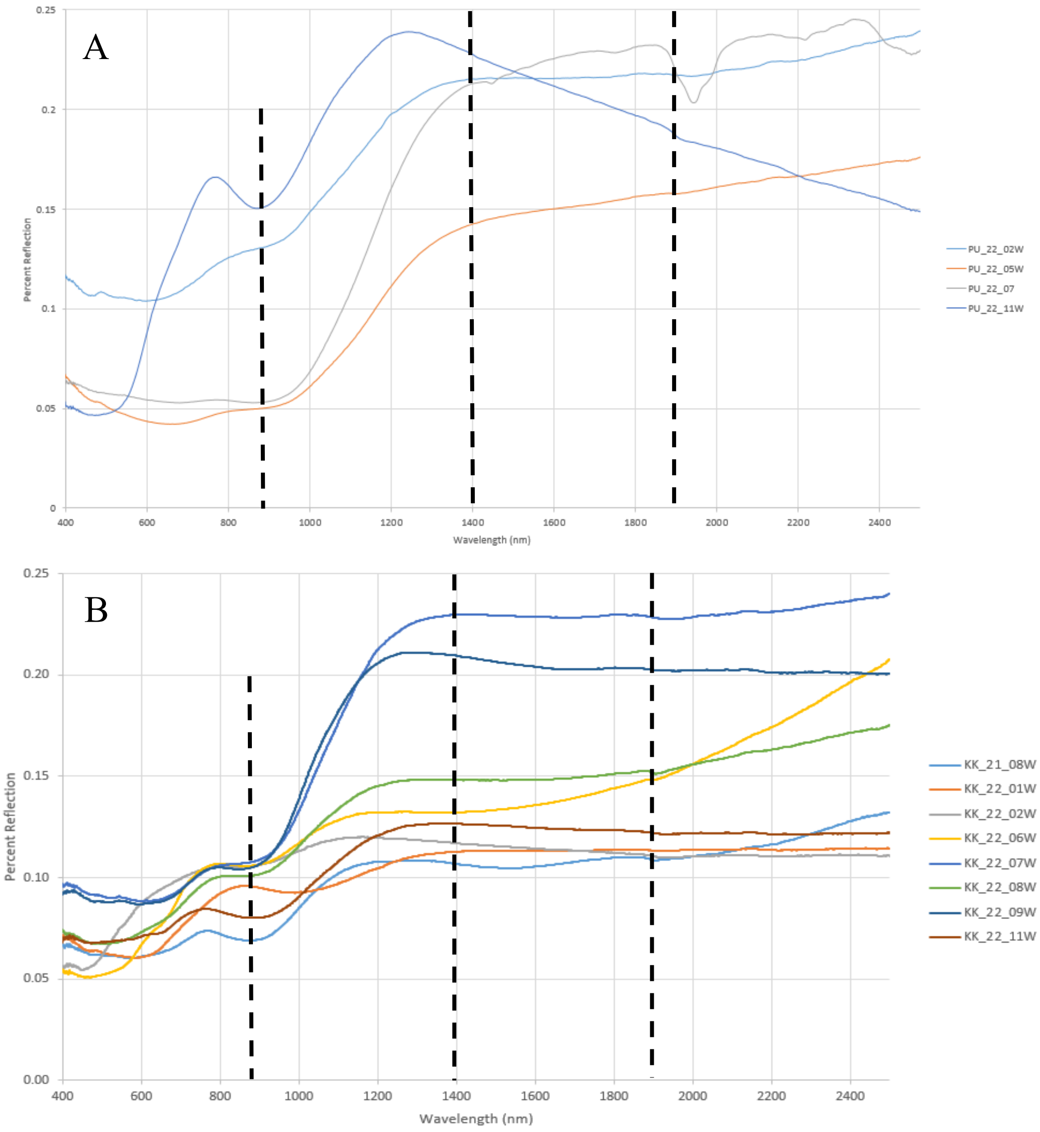

Figure 3 Visible-Near Infrared spectral reflectance curves of sample surfaces from (A) Puʻuʻōʻō and (B) Kipuka K. Dashed lines at 870 nm represent a characteristic absorption band for ferric iron, while dashed lines at 1400 and 1900 nm are characteristic of water.

Discussion

X-ray diffraction Anorthite, augite, ilmenite and hematite are present in both substrate samples. Magnesioferrite, cristobalite, tridymite, and gypsum are present in the KK and PU lava tube systems, but not the substrates, suggesting they formed by processes within the lava tubes. Magnesioferrite is known to form in lava tubes during the active stage (Sawlowicz, 2020). During the active stage, the surfaces of walls and ceilings have fluctuating temperatures near and above the basalt solidus (~985-1080°C; Helz et al., 2003). Tridymite and cristobalite are high-temperature polymorphs of quartz. It is likely these minerals formed during the active stage and/or the start of the cooling stage with magnesioferrite. Gypsum is a common mineral deposit in lava tubes (White, 2010). A variety of sulfate minerals form during the active and cooling stages. However, when the lava tube cools enough, meteoric water enters and removes the more soluble sulfates (Sawlowicz, 2020). The gypsum found in our samples may have formed during the cooling stage, or formed in place of a more soluble sulfate when it interacted with water. Hematite can form in a variety of oxidizing conditions. Future research with SEM analysis will attempt to distinguish if hematite formed in a high or low temperature oxidation environment.

Visible-near infrared spectroscopy The ferric iron absorption feature present in each sample's spectral signature can be explained by the several iron oxide minerals identified through XRD. The presence of OH bonds is found in the only sample with gypsum present (PU_22_07). The OH bonds and large amounts of water present in this sample are likely a measurement from the gypsum ($CaSO_4 \cdot 2H_2O$). This would also indicate why such features aren't present in any of the other spectral signatures. The small absorption features for water present in the other samples may be from any moisture remnant from meteoric water.

Preliminary Conclusions

While data collection is ongoing and much is still to be learned, current evidence suggests that the predominant mineral assemblage of lava tube samples formed near or above the current average surface temperature of Venus. The dynamic nature of a lava tube means that certain minerals expected to be on Venus, like anhydrite, are present within lava tubes for a limited time until temperatures are low enough for meteoric water to enter and remove them. The composition of the lava and local climate appear to also influence how Venus-like a lava tube is. Ongoing and future research will better characterize these conditions. When complete, the data collected here may inform researchers of upcoming Venus missions like NASA's DAVINCI (Garvin et al., 2022), VERITAS (Smrekar et al., 2022), and ESA's EnVision (Ghail et al., 2018).

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