SOIL-FORMING PROCESSES ON MARS AS DETERMINED BY MINERALOGY: ANALYSIS OF RECENT MARTIAN SPECTRAL, CHEMICAL AND MAGNETIC DATA AND COMPARISON WITH ALTERED TEPHRA FROM HALEAKALA, MAUI.

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Minerals such as sulfates, phyllosilicates, and iron oxides/oxyhydroxides (FeOx) are good indicators of soil formation processes and have all been identified on Mars. Here we apply integrated analyses of data from recent missions and alteration of tephra at Haleakala crater, Maui, to soil formation processes on Mars. This tephra contains amorphous silica, jarosite, FeOx, phyllosilicates, a magnetic component, and some samples exhibit a mid-IR doublet very similar to that observed for the Martian soil.

Introduction: Martian soil measured at the Viking and Pathfinder sites, Gusev crater, Meridiani Planum and globally via imaging spectrometers show many similarities suggesting that substantial mixing has taken place on the surface of Mars [e.g. 1,2]. However, subtle variations in chemistry indicate contributions from local environments to the soil formation processes on Mars [e.g. 3,4]. In particular, the presence of sulfates and phyllosilicates in multiple specific sites are indicators of aqueous processes [5,6,7] and are likely to have been sites of active soil formation processes at one point in Mars' history.

The soil on Mars has long been known to be dominated by Si and Fe [8] and to be magnetic [9]. Early elemental analyses suggested the presence of smectite, kieserite, hematite, and magnetite [10]. However, unique identification of these minerals on Mars has only recently been possible [e.g. 5,11,12]. Based on (i) analysis of terrestrial volcanic alteration sites [e.g. 13,14,15], (ii) current identifications of kieserite, gypsum, polyhydrated sulfates, smectites and other phyllosilicates in selected Martian outcrop regions, and (iii) a lack of unique sulfate and phyllosilicate identifications in the Martian soils, it is likely that the Martian soil units contain poorly crystalline and/or amorphous sulfate and phyllosilicate components.

Magnetic [9,16] and Mössbauer measurements [11] have constrained the FeOx components in the Martian soil. The magnetic properties suggest the presence of maghemite intermixed with phyllosilicate and/or amorphous silicate grains [9,16] or Ti-magnetite intermixed with amorphous silica [17]. The former interpretation is consistent with a greater degree of aqueous processes on Mars than the latter. Modeling of Mössbauer spectra suggests the presence of silicates, hematite, magnetite and jarosite [11, 12].

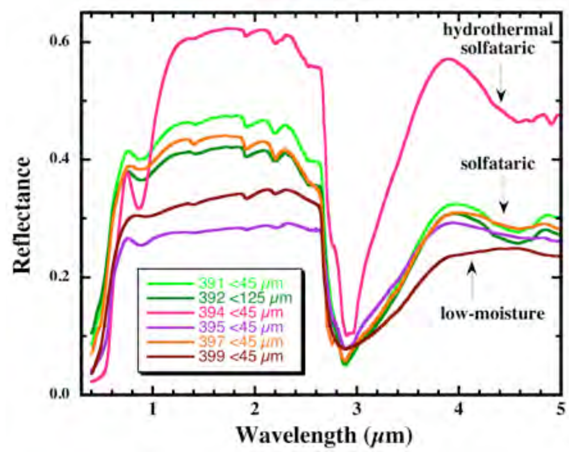

Fig. 1 VNIR spectra of Haleakala samples.

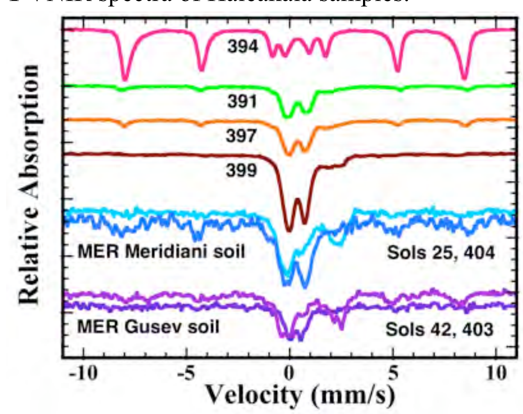

Fig. 2 Mössbauer spectra of Haleakala samples (295K) and Martian soils (260-280 K).

Altered Tephra at Haleakala, Maui: The unaltered basaltic tephra at Haleakala contains feldspar, pyroxene, olivine, and glass. Altered tephra include material exposed to gradual, low-moisture weathering (brownish color), hydrothermally altered material at the rims of cinder cones (bright red), and solfatarically altered material (yellow-orange color) near cinder cones. All samples reacted to a hand-held magnet and those at the crater rim are substantially more magnetic.

Low-moisture alteration environment. Most of the altered Haleakala ash/tephra have been exposed to low-moisture long-term weathering (#399). XRD of this material shows the presence of feldspar, pyroxene and magnetite. SEM and TEM studies found glass and amorphous phases in altered grains and rinds, as well as fresh pyroxene and olivine grains in tephra fragments. VNIR (Fig. 1) and Mössbauer spectra (Fig. 2) exhibit differences between the low moisture and solfataric alteration of this tephra.

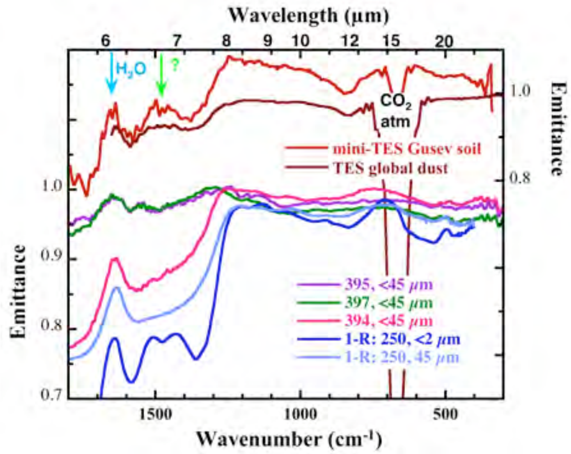

Fig. 3 Mid-IR emission and reflectance spectra of Mars [18,19] and Haleakala samples.

Solfataric alteration environment. The crater rim samples (#250, 394, 395) have a much greater Fe abundance (up to 50% Fe_2O_3) and were formed under high temperature hydrothermal conditions with sulfuric fumes. XRD, Mössbauer and VNIR spectra of these samples indicate the presence of hematite, magnetite, maghemite, alunite-jarosite, and phyllosilicate along with some residual primary silicates and glass. Mid-IR spectra of these samples also show a broad band near the 1630 cm^{-1} H_2O feature and the <2 µm fraction exhibits a doublet very similar to that observed by TES in the global Martian soil [18] and mini-TES in the Gusev and Meridiani soil [19]. This feature is also observed for hydrous sulfates [20] and hydrated iron oxides [21].

Additional samples collected near the cinder cone (#391, 392, 397) contain elevated Fe and S levels compared to the bulk of the altered tephra material, but not as high as the altered material directly on the rim of the crater. SEM analyses of these samples show the presence of Fe oxide and Al sulfate in surface rinds and silica layers in near surface layers of the tephra. TEM shows glass, fibrous clay-like material, amorphous Si-Al-Fe material, and alunite-jarosite grains in these samples. Mössbauer and VNIR spectra contain evidence of alunite-jarosite in these samples. VNIR bands near 2.2-2.3 µm are also consistent with some phyllosilicates.

Applications to Mars. The altered tephra from Haleakala may represent on a small scale an example of the soil formation processes on Mars. In this environment the bulk of the altered ash/tephra deposit is altered via a gradual, low-moisture process. Small, isolated regions of soil and tephra units contain sulfates, phyllosilicates and elevated abundances of FeOx. These minerals are indicators of solfataric alteration in the Haleakala crater environment and could be indicators of aqueous and solfataric alteration processes on Mars. Over time wind has mixed the soil/dust particles at Haleakala and components of the sulfate-, phyllosilicate-, FeOx-rich material has spread throughout the crater and enriched the S in the altered (low-moisture) tephra compared to the solfataric tephra. Extended visible region spectra (Fig. 4) of low-moisture and solfataric material are consistent with Martian soils.

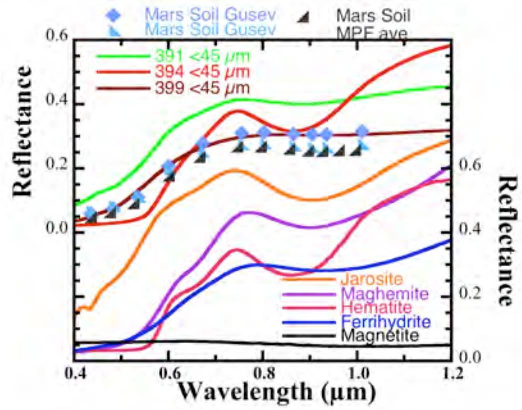

Fig. 4 VNIR spectra of Haleakala samples compared to minerals and Martian soil spectra [22,23].

The hydrous component responsible for the puzzling mid-IR doublet is found here in the finest fraction of the hydrothermally altered material. A similar process on Mars could have produced this feature in isolated regions, then been spread via dust storms. As a large amount of material on Mars is finely particulate (2-3 µm diameter), the component in the <2 µm fraction of the hydrothermally altered Haleakala material could be more ubiquitous on Mars and sufficiently abundant to produce the mid-IR doublet widely observed in soil spectra.

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