Olivine dissolution by acidic fluids in Argyre Planitia, Mars: Evidence for a widespread process?

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ABSTRACT

Compositional and morphological analyses of basin rim units in Argyre Planitia are consistent with local olivine-rich materials that become relatively olivine-poor in the process of being transformed from rocky materials to finer particulate regolith. Where high-thermal-inertia rocky surfaces are observed, the composition is more mafic than the surrounding fines. This relationship between rocks and soils appears to be common on Mars as a similar pattern is observed in other locations, such as Gusev Crater, Isidis Planitia, and Nili Fossae. Despite the lack of local detectable alteration products, these trends may be an indication that most Martian dark regions are not similar in composition to the primary igneous composition from which they are derived. The Martian crust may be significantly more mafic, and alteration of these surfaces may be more pervasive than has been inferred from the bulk surface mineralogy derived from orbital observations.

Keywords: Mars, alteration, infrared spectroscopy, regolith formation, surface composition.

INTRODUCTION

The Martian meteorites and many geochemical and spectroscopic data sets have been used to investigate the compositional diversity of Mars. These investigations have led to the identification of a number of geochemical and mineralogical signatures that have provided clues about the igneous and water-related history of Mars. This includes identification of minor carbonates, isolated regions that contain concentrations of sulfates, hematite, amorphous silica, and phyllosilicates, and the ubiquitous presence of oxidized iron (e.g., Singer et al., 1979; Bell et al., 1990; Gooding, 1992; Christensen et al., 2000; Bandfield et al., 2003; Poulet et al., 2005; Bibring et al., 2005; Ming et al., 2006; Morris et al., 2006; Glotch et al., 2006). These compositions have been used to define the limited extent of aqueous alteration of the Martian crust. The identification of other minerals, such as quartz, plagioclase, pyroxene, and olivine have been used to characterize Martian igneous processes and potential complexities of their formation mechanisms (e.g., Adams and McCord, 1969; McSween, 1994; Bandfield et al., 2000; Hamilton et al., 2003; Hoefen et al., 2003; Bibring et al., 2005; Mustard et al., 2005; McSween et al., 2006a, 2006b; Ruff et al., 2006; Bandfield, 2006; Rogers and Christensen, 2007).

There has been vigorous debate regarding the formation mechanism of some Martian surface compositions. However, low-albedo regions composed primarily of plagioclase, pyroxene, and olivine have been widely presumed to be unaltered basalt (e.g., Bandfield et al., 2000; Bibring et al., 2005; Mustard et al., 2005; Rogers and Christensen, 2007). Compositional and morphological analyses presented here demonstrate that this presumption is incorrect in isolated locations and may be generally incorrect planetwide. This is supported by previous laboratory experiments and Mars Exploration Rover (MER) investigations within Gusev Crater (e.g., Tosca et al., 2004; Hurowitz et al., 2006; McSween et al., 2006a). Soil formation on Mars may involve significant alteration of the source lithology, dominated by the dissolution of olivine by acidic fluids. "Soil," as used here, is the finer fraction of the regolith and does not imply organic content. Confidence in the interpretation of surface formation processes is bolstered by the ability to examine spatial and morphologic relationships between compositions at high resolution.

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DATA SETS

Several data sets were examined, including the Mars Global Surveyor Thermal Emission Spectrometer (TES) (Christensen et al., 2001) and Mars Orbiter Camera (MOC) (Malin and Edgett, 2001), Mars Odyssey Thermal Emission Imaging System (THEMIS) (Christensen et al., 2004), and the Mars Express Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité (OMEGA) (Bibring et al., 2005). The visible-wavelength imaging data sets (MOC and THEMIS VIS) were used to characterize surface morphology at 1.5–18 m/pixel. Nighttime THEMIS surface temperature images were used to derive thermal inertia, which is an indicator of surface cover particle size (e.g., Fergason et al., 2006). Spectroscopic data sets were used to derive surface mineralogy based on the position and shape of spectral absorption features present from near-infrared through thermal-infrared wavelengths (0.9–50 µm). These data sets were calibrated, atmospherically corrected, and analyzed using methods described by Smith et al. (2000), Bandfield et al. (2004), and Pelkey et al. (2007). Specifically, low-spatial-resolution (~3 by 8 km sampling) but high-spectral-resolution (143 spectral channels from ~7 to 50 µm) TES data were used to obtain the detailed bulk mineralogy of large-scale compositional units. Higher-spatial-resolution (100 m/pixel) multispectral (nine spectral channels from 7 to 15 µm) THEMIS imaging data were used to define surface compositional units and establish their spatial relationships. OMEGA near-infrared spectra (0.9–2.5 µm at >400 m sampling) were used to identify iron-bearing minerals, sulfates, and phyllosilicates that may be present in minor quantities. In addition, results were incorporated from other studies that used data from the MER Miniature Thermal Emission Spectrometer (Mini-TES) and Panoramic Camera (Pancam).

RESULTS

Morphological and Thermophysical Analyses

Figure 1 displays THEMIS infrared data acquired over the northeast portion of Argyre Basin, near 330°E, 45°S. The region consists of isolated hills surrounded by flat plains. The albedo of relatively dark and bright surfaces within the region is 0.15 and 0.16, respectively. All surfaces are considered dark and relatively free of obscuring dust cover.

Several hills in the region appear relatively warm in nighttime THEMIS infrared imagery, indicating a higher thermal inertia consistent with rockier surfaces or limited exposures of bedrock. The warmer surfaces have a thermal inertia of 550 J m^{-2} K^{-1} $s^{-1/2}$, and the surrounding regions have values of ~300–350 J m^{-2} K^{-1} $s^{-1/2}$. These observations are consistent with rocky surfaces surrounded by a regolith dominated by finer particulates.

Several high-resolution MOC images are available within the region. These images display a prevalence of gullies (Malin and Edgett, 2000) on the northern and eastern slopes of the higher-thermal-inertia surfaces of the isolated hills. The gullies have incised into the hills, and the sediment transport paths lead from the rocky surfaces to the surrounding relatively flat terrain that is dominated by fines (Fig. 2).

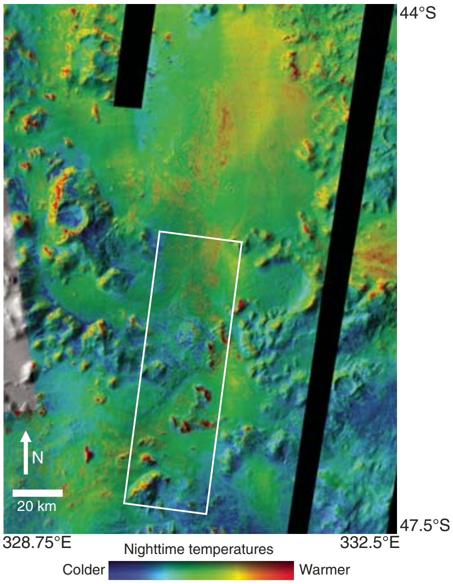

Figure 1. Infrared mosaic of the region in northeast Argyre Planitia discussed in the text. Daytime infrared measurements are used for shading, and nighttime infrared measurements are displayed in the color scale. Nighttime temperatures indicate relative values of thermal inertia within the region. The white box indicates the region shown in Figure 3.

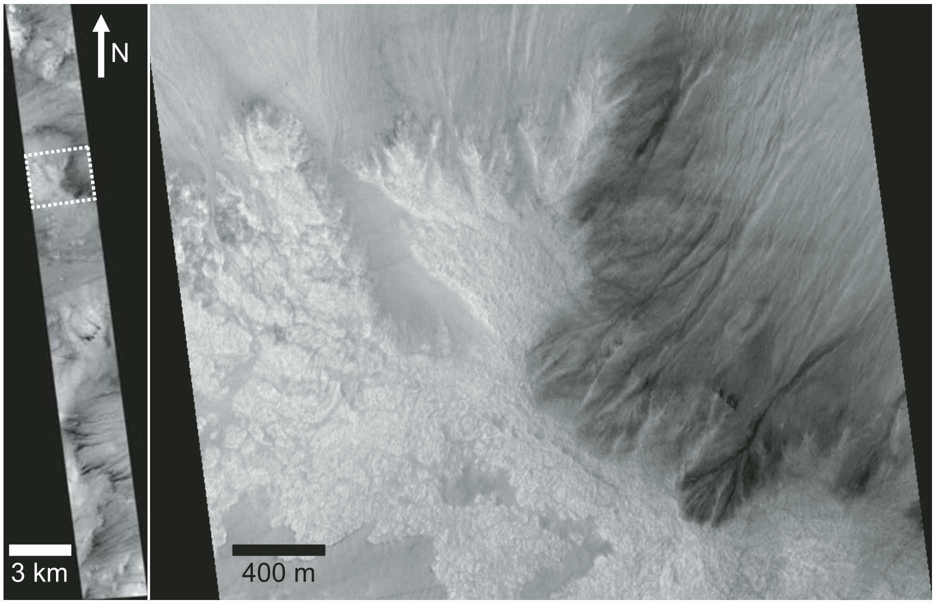

Figure 2. Portion of Mars Orbiter Camera (MOC) image E1104337 for the area denoted in Figure 3. The dotted box in the left image shows the region of detail on the right. Olivine-rich high-inertia regions are coincident with the textured relatively high-albedo surfaces. Smoother surfaces and incised gullies are coincident with olivine-poor surfaces. Although the albedo differences appear to be large, especially in the areas with gullies, they are only ~0.01 and are similar to other regions, such as Nili Patera where sediments are slightly darker than bedrock surfaces.

Spectral and Mineralogical Analyses

False-color THEMIS images show indigo, orange/red, and green/yellow colors that correspond to three primary spectral units within the region (Fig. 3). The indigo spectral unit is coincident with the rockier surfaces and has spectral absorption features at relatively long wavelengths (10–12 µm). The indigo unit is not spatially extensive enough to be resolved with TES data. The orange/red spectral unit is commonly located within local depressions in the hilly terrain and on the slopes and bases of the hills. This spectral unit, with absorption features centered at relatively short wavelengths (~9–11 µm) is dominated by fines and is similar to larger low-albedo plains surfaces within the region. The green/yellow spectral unit is similar to the orange/red spectral unit, but has shallower spectral absorption features. The green/yellow and orange/red spectral units are spatially extensive enough to be resolved with lower-spatial-resolution TES data (Fig. 3); TES-derived spectral shapes of these units are consistent with the THEMIS results. None of the publicly available OMEGA images within the region was acquired with favorable incidence angles for robust spectral analysis (<60°). Only the monohydrated mineral and orthopyroxene mineral detection indices (Pelkey et al., 2007) showed positive detections, which coincided with the relatively low-albedo regions and the orange/red spectral units.

The indigo unit with relatively long-wavelength spectral absorption features is similar to more spatially extensive olivine-rich surfaces present in other Martian regions, such as Nili Fossae and Ares Valles (Hoefen et al., 2003; Hamilton et al., 2003; Rogers et al., 2005; McSween et al., 2006a). Deconvolution of the measured spectra to find the relative weighting of mineral component spectral signatures indicates that those surfaces have up to ~35% olivine by volume with associated pyroxene and plagioclase. The shorter-wavelength spectral absorption features characteristic of the orange/red spectral unit are consistent with surfaces of higher SiO_2 contents relative to the indigo unit surfaces (e.g., Salisbury and Walter, 1989). The spectral absorption features present between ~22 and 26 µm (380–450 cm^{-1}) in the TES spectra are diagnostic of the presence of olivine, but at lower concentrations than the indigo unit. The green/yellow spectral unit is similar in shape to the orange/red spectral unit, but without clear identification of the diagnostic olivine spectral features. These observations suggest that the primary difference between the three units is their relative olivine content, with the indigo unit having the highest abundance and the green/yellow unit having the lowest abundance. The shallow spectral absorption features and the slightly higher albedo of the green/yellow spectral unit are consistent with minor dust contribution or finer particle size.

The OMEGA data, in addition to the TES data, show little clear indication of alteration products within the region. The low-albedo regions that coincide with the THEMIS orange/red spectral unit show a slight 2.1 µm spectral absorption feature characteristic of monohydrated sulfate (Gendrin et al., 2005). However, the lack of a corresponding 1.6 µm hydration feature, along with the fact that the image was acquired under nonideal solar incidence angles (>70°), make this feature suspect. Olivine, high-Ca pyroxene, low-Ca pyroxene, and phyllosilicates have been identified in unreleased OMEGA data covering the northern rim of Argyre Basin (Buczkowski et al., 2007). However, phyllosilicates or other secondary alteration products were not identified in the northeast portion discussed here.

DISCUSSION/CONCLUSIONS

The observations in Argyre Planitia are consistent with local olivine-rich materials that become relatively olivine-poor in the process of being transformed from rocky materials to finer particulate regolith (Fig. 2). The gullies present in the region appear to incise directly into the olivine-rich rocky surfaces and show a clear transport pathway for mechanically weathered materials that leads from the one composition to the other. This pattern is observed throughout the region. Where high-inertia rocky surfaces are observed, the composition is more mafic than the surroundings and consistent with olivine-rich surface mineralogies. The lower-inertia regolith present throughout the region is consistent with a relatively olivine-poor basaltic mineralogy.

This relationship between olivine-rich rocks and olivine-poor soils appears to be common on Mars. For example, this pattern is observed

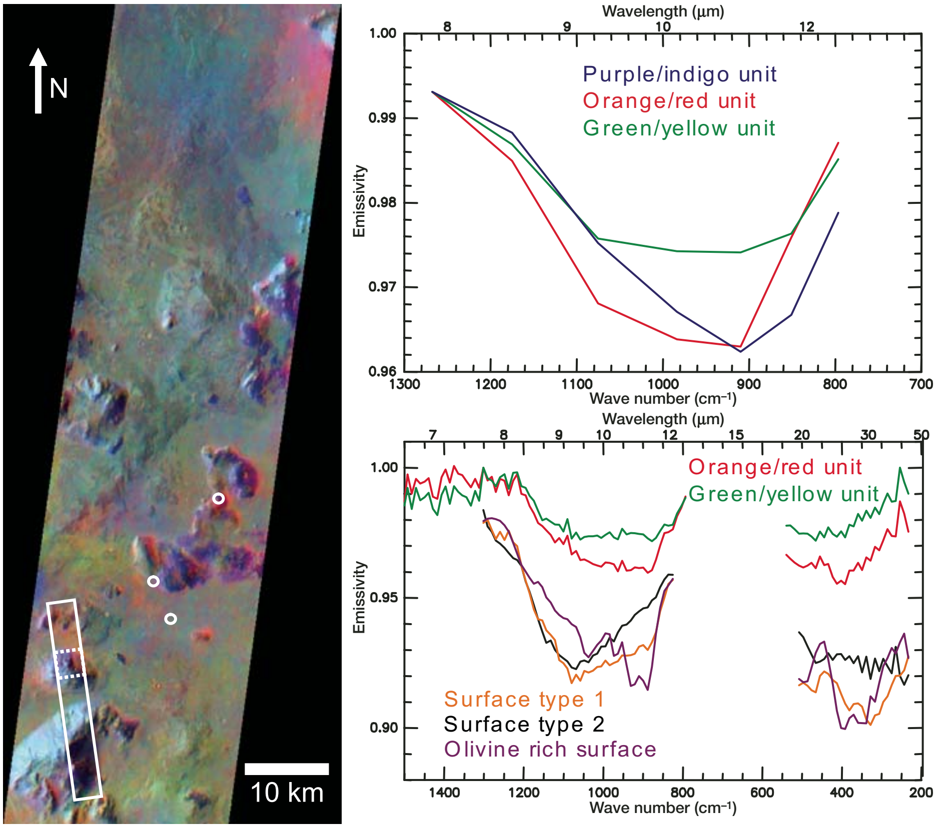

Figure 3. Mars Odyssey Thermal Emission Imaging System (THEMIS) decorrelation stretch image (I08228004) using radiance in bands 8, 7, and 5 projected as red, green, and blue, respectively. The atmospherically corrected THEMIS spectra denoted by the white circles are shown in the top plot. More extensive orange/red unit and green/yellow unit surfaces are present in regions such as near the top of the image, and the atmospherically corrected Mars Global Surveyor Thermal Emission Spectrometer (TES) data for these regions are shown in the bottom plot. TES spectral surface types 1 and 2 from Bandfield et al. (2000) and an olivine-rich surface spectrum from Nili Fossae are shown for comparison. The white box in the image indicates the region shown in Figure 2.

in THEMIS data that cover regions such as Ares Valles, Valles Marineris, Nili Fossae, and the southern rim of Isidis Planitia. Mini-TES observations within the plains of Gusev Crater show that the rocks are dominated by the olivine-rich (~40 areal percent) Adirondack class basalts (Ruff et al., 2006). Yen et al. (2005), using both Mini-TES and Mössbauer data, noted that the dark, basaltic soils within the Gusev plains have a relatively olivine-poor mineralogy (~15 areal percent; Fig. 4). These trends may be an indication that most Martian dark regions are not representative of the primary igneous composition from which they are derived and that the Martian crust is significantly more mafic than had been inferred from the bulk surface mineralogy derived from TES observations. McSween et al. (2006a) have also speculated that primitive magmas such as picritic basalts may be more common than generally accepted based on the compositional relationships at Gusev Crater and elsewhere.

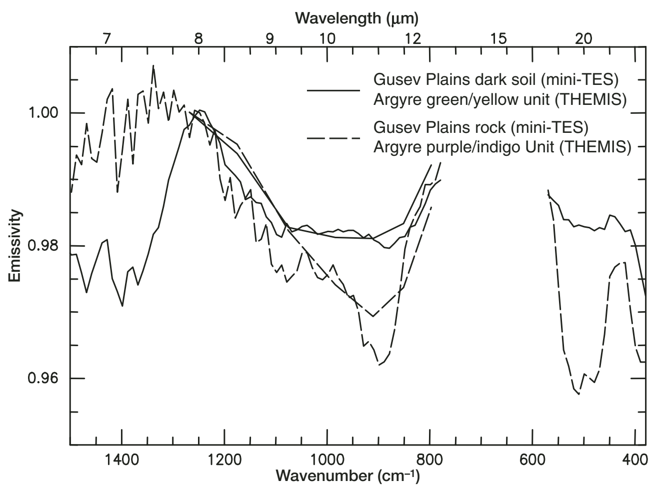

Figure 4. Miniature Thermal Emission Spectrometer (Mini-TES) and Mars Odyssey Thermal Emission Imaging System (THEMIS) spectra of olivine-rich rocks or rocky surfaces and olivine-poor soils. The spectral contrast has been adjusted to match the depth of features to compare the spectral shapes. THEMIS spectra are the same as shown in Figure 3. The Gusev plains dark soil (named Dress) is similar to that shown in Yen et al. (2005). The Gusev plains rock (Sarah) spectrum is taken from Ruff et al. (2006).

The most likely mechanism for generation of olivine-poor soils from olivine-rich rocks is alteration by acidic fluids. Tosca et al. (2004) and Hurowitz et al. (2006) have shown that the dissolution of olivine is a rapid process in a low-pH, water-limited environment similar to current Martian near-surface conditions. Hurowitz et al. (2006) found the Martian soils at Gusev Crater to be consistent with alteration at low pH and low water-to-rock ratios, resulting in weathering dominated by olivine dissolution and subsequent precipitation of Fe oxides, amorphous silica, and sulfate phases. The spatial and geochemical/mineralogical relationships between the rocks and soils on Mars are consistent with widespread dissolution of olivine in an acidic aqueous environment under conditions that could have occurred in the recent Martian past (e.g., Hurowitz et al., 2006). It is likely that the secondary Fe oxides, sulfates, and amorphous silica expected in such a weathering regime are present in the soils, but these products can be difficult to confidently detect in the orbital spectral data sets. Detailed analysis of dark soils in Meridiani Planum using MER data indicates that sulfate and amorphous silica components are likely to be present (Rogers and Aharonson, 2008).

The data that we have presented concern compositions dominated by plagioclase feldspar and pyroxene that occur throughout the southern highlands (similar to global surface type 1 of Bandfield et al., 2000). Inferences made regarding Martian igneous compositions from orbital spectroscopy may require complex interpretations that account for subsequent alteration (though prior to the availability of high-resolution geologic context, it is arguable that simple interpretations were the most appropriate). Variations in mineralogy throughout Martian dark regions, including surface type 1 areas, may be as much representative of alteration as variations in primary composition.

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