Evidence for extensive olivine-rich basalt bedrock outcrops in Ganges and Eos chasmas, Mars

C. S. Edwards,1 P. R. Christensen,1 and V. E. Hamilton2

Received 22 January 2008; revised 24 July 2008; accepted 5 August 2008; published 6 November 2008.

[1] Several localized outcrops of olivine-enriched bedrock have been previously identified in the Ganges and Eos Chasma area on the eastern end of Valles Marineris with the Thermal Emission Imaging System multispectral images. These outcrops form a layer in the walls of Ganges Chasma and appear to be the remnants of a once continuous unit, which was mapped over ~100 km. In this study we further characterize the composition (forsterite content of ~0.68), olivine abundance (10 to >15%), thermal inertia (>600 JK−1 m−2 s−1/2, consistent with in-place rocky material), vertical dimension (~60 to ~220 m), extent (>1100 km laterally), volume (~9.9 × 106 km3), dip (~0.013°NE), and continuity of this layer utilizing Thermal Emission Spectrometer hyperspectral, Thermal Emission Imaging System multispectral, and Mars Orbiter Laser Altimeter elevation data. Morphologic data from high-resolution imagery display a relatively unmannetd, rough, and pitted surface associated with the olivine-enriched material, consistent with thermal inertia data. Four possibilities for the origin of the olivine-enriched unit are (1) volcanism associated with tectonic rifting of the Valles Marineris system, (2) a volcaniclastic flow deposit, (3) an intrusive mafic sill, or (4) a discrete episode in Martian history during which flood lavas were erupted onto the surface. The most likely origin is an eruptive event consisting of compositionally uniform flood lavas originating from a primitive mantle source region, possibly associated with the initiation of Tharsis volcanism. This unit is one of the largest continuous compositional units found on Mars and is strikingly similar to other olivine-enriched deposits identified in previous studies where compositional, morphologic, and thermophysical similarities are observed. These similarities may indicate that there was a period in early Martian history, where compositionally uniform and extensive olivine-enriched flood basalts were erupted on the Martian surface.


1. Introduction

[2] Mars is a planet whose surface is dominated by basalt in the southern highlands, and basaltic andesite or weathered basalt in the northern lowlands [e.g., Bandfield et al., 2000; Wyatt and McSween, 2002], which have been further characterized into four primary subcomponents [Rogers and Christensen, 2007]. However, on a local scale, the Martian surface displays a wide range of volcanic compositions including olivine-enriched basalt [Christensen et al., 2003; Hamilton et al., 2003; Hoefen et al., 2003; Hamilton and Christensen, 2005; Mustard et al., 2005; Rogers et al., 2005; McSween et al., 2006; Tornabene et al., 2008] and more felsic materials such as dacite observed in the Syrtis Major caldera [Christensen et al., 2005]. Although many areas have been characterized by their compositional data and physical nature, the detailed distribution of differing volcanic rock units discovered to date has not been fully investigated. Of particular interest is the occurrence and distribution of olivine-enriched basalts in space and time. Olivine-enriched units have been identified globally and in situ [Mustard et al., 2005; McSween et al., 2006; Rogers and Christensen, 2007; Koeppen and Hamilton, 2008; Tornabene et al., 2008] but their spatial and temporal relationships remain uncertain.

[3] Several localized outcrops of olivine-enriched bedrock have been previously identified in the Ganges and Eos Chasma area on the eastern end of Valles Marineris with the Thermal Emission Imaging System (THEMIS) onboard the 2001 Mars Odyssey Spacecraft [Christensen et al., 2003; Hamilton et al., 2003; Hamilton and Christensen, 2004]. These outcrops form a ~50 m thick layer exposed in the walls of Ganges Chasma, and appear to be the remnants of a once continuous unit that was mapped over a ~100 km distance using THEMIS multispectral images [Christensen et al., 2003]. Thermal Emission Spectrometer (TES) spectra...
show this unit to be an olivine-enriched basalt with 10–15% olivine abundance with a composition of forsterite content of ~0.68 (Fo68) [Christensen et al., 2003].

Several questions have arisen since the initial identification of these olivine-enriched basalt outcrops. Has olivine rich material formed continuously throughout Martian history, was it an episodic event, or was it emplaced in a limited time range or locality? Also, is the Ganges unit continuous and if so, what is its extent? How does this unit relate to other olivine-enriched locations on Mars? THEMIS infrared multispectral data provide excellent means to address several of these issues because of the high spatial resolution, the nearly global coverage, and their strong ability to discriminate olivine-bearing materials. When THEMIS data are used in conjunction with other data sets (e.g., TES and Mars Orbiter Laser Altimeter (MOLA) data), constraints on the lateral extent, the stratigraphic distribution, olivine abundance, and composition can be made. However, the full extent of this unit may be unmatchable with this technique in areas of high dust cover (as dust easily obscures the underlying bedrock composition at thermal infrared wavelengths [Ruff and Christensen, 2002]) to the north and west of Ganges Chasma where exposures are lacking.

2. Method

In order to assess the spatial distribution of the Ganges and Eos Chasma olivine-enriched deposits, we created a false color mosaic of THEMIS multispectral daytime infrared data at 100 m per pixel spatial sampling, using bands 8, 7, and 5 (11.79, 11.04, and 9.35 μm respectively). We chose these bands to emphasize the strong absorption in band 7 due to olivine [e.g., Christensen et al., 2003] that is lacking in the surrounding basalt units. A decorrelation stretch [Gillespie et al., 1986] was performed on the multiband mosaic to emphasize spectral differences; using the 8, 7, and 5 band combination, the olivine-enriched unit appears purple. We extended the mosaic in all directions until the olivine-bearing unit could no longer be identified, with the mosaic eventually covering an area of approximately 1.2 × 106 km2 (Figure 1).

THEMIS data up to Mars Odyssey orbit ~25,000 were used in this study, as there were no significant dust storm events up to this time during the Mars Odyssey mission and atmospheric dust content remained low and relatively uniform. The variations in atmospheric dust content in the data used for this study are small enough that they can be ignored and no atmospheric correction needs to be performed on the THEMIS data. Also, because this olivine-enriched unit typically occurs within ~200 m of the relatively flat canyon floor, the atmospheric path lengths of this unit and the surrounding floor material vary by less than ~10%. This is important for determining the composition of the outcrops, as we assume that the only difference between the olivine-bearing unit and the surrounding material is the presence or absence of olivine. This assumption can only hold true if the atmospheric path lengths are similar; as the path length increases more atmospheric signal is included in the spectrum making direct comparisons difficult. In this study, comparisons have only been made where path lengths are relatively similar (typically <200 m difference), precluding comparisons between the floor of Valles Marineris and the surrounding plateau.

Nighttime temperature is a good proxy for thermal inertia where warm (e.g., 200 K) material corresponding to high thermal inertia material (e.g., >600 JK−1 m−2 s−1/2) is more consolidated and/or rockier than colder material (e.g., 185 K, 200 JK−1 m−2 s−1/2), such as dust or sand deposits [e.g., Pallucconi and Kieffer, 1981; Mellon et al., 2000; Putzig et al., 2005]. We calculated thermal inertia for individual THEMIS images following the method described by Ferguson et al. [2006], which uses the KRC thermal model (H. H. Kieffer, Thermal models for analysis of Mars infrared mapping, manuscript in preparation, 2008), for several of the outcrops under investigation. We created a 100 m per pixel nighttime temperature mosaic (Figure 2), which allowed for another method to help identify rockier locations commonly associated with olivine-enriched outcrops. These rockier outcrops are likely indicative of in situ, stratigraphically significant materials, which are the focus of this study. Although these large-scale mosaics were useful for identifying potential outcrop locations, we manually validated the location of outcrops using both individual daytime and nighttime THEMIS images. This was necessary as these mosaics are composed of individually stretched images and not the actual radiance and thermal inertia data respectively. Additionally, this hand validation allowed for the calibration (e.g., low time duration between the shutter closing calibration image and data acquisition, low atmospheric dust opacities) and data quality (e.g., high signal to noise, warm images) to be assessed.

We are able to identify the olivine-enriched unit locally on the basis of its thermal inertia, with a typical range of ~400 to ~600 JK−1 m−2 s−1/2 and greater. Many of the unit’s outcrops have much higher thermal inertia than the surrounding floor material and can also have an extremely high thermal inertia (>1200 JK−1 m−2 s−1/2). Several of these outcrops have been classified as a high inertia surface by Edwards et al. [2005], indicating that this material is consistent with in place rock. Materials with high thermal inertia have more significant implications for the geologic history of the area than if the thermal inertia were that of unconsolidated mobile sediments. However, all high thermal inertia materials may not be composed of olivine-enriched basalt, requiring the consideration of multi and hyperspectral data to accurately identify the composition of these outcrops. We mapped out the locations of olivine-bearing outcrops on a background daytime infrared mosaic after they were identified on the original multispectral mosaic, nighttime temperature mosaic and subsequently confirmed through the analysis of individual images. Two examples of smaller decorrelation stretch mosaics are shown in Figures 1b and 1c.

The composition of the olivine in some of these units was constrained by Christensen et al. [2003] and Hamilton et al. [2003] using two different approaches. Christensen et al. [2003] ratioed a TES spectrum from a prominent olivine-enriched outcrop to a spectrum of the nearby canyon floor and showed that the resulting spectral shape is a good match to Fo68 olivine. They concluded that this unit is an olivine-enriched basalt with 10–15% olivine. Hamilton et al. [2003] used Martian meteorite spectra and TES-derived Martian surface spectra to model TES spectra of Mars and
identified these areas as basaltic with components (concentrations up to 20%) that are matched by the Martian meteorites Chassigny and ALH 77005, both of which contain large amounts of Fo68 olivine. In this paper, we took an approach similar to that of Christensen et al. [2003] and have examined several outcrops (5 locations with the best data coverage, where TES footprints covered a large fraction (>60%) of the location in question and highest data quality, where the warmest (250–300 K), lowest atmospheric opacity (both dust and ice), nadir looking spectra were used to study the composition of this unit over its full extent.

[10] After we identified and mapped all of the outcrops, we registered Mars Orbiter Laser Altimeter (MOLA) elevation data for both gridded and ground track(s) elevation data [Smith et al., 2001] to the compositional data. We determined the average elevation of approximately 60 of the largest most prominent outcrops from the gridded elevation data on the basis of locations identified in Figure 1. We also examined single point elevation data to ensure that the gridded values were representative of the actual outcrop elevations. Additionally, estimates for the thicknesses of these outcrops have been made through the use of both gridded MOLA elevation data and ground track data where available. The outcrop thicknesses are estimated from the minimum and maximum elevations of each outcrop and the standard deviation of the elevation for all of the individual gridded outcrop elevations. However, these thicknesses should be considered minimum thicknesses, as it is not possible to determine the extent to which these units extend downward or the extent to which they have been eroded.

[11] We created several topographic cross sections (Figures 3a–3d) to determine if exposures were laterally continuous (indicating that they are all part of the same unit) and if so, to determine the orientation of that unit. However, because most of average elevation data for individual outcrops did not lie directly along each topographic profile, a different approach was required. The
average outcrop elevation for each of these locations was extracted (a maximum of up to \( \sim 50-80 \) km away from the topographic profile line) and then projected orthogonally to the defined topographic cross section line. This method allows for a generalized depiction of outcrop elevation in relation to general topography. If the topographic line crosses a high or a low point in the canyon, such as a hill or crater, and outcrops are in the canyon walls, the relationship between the outcrop elevation and the topographic profile line may not be well represented. For example, in the aforementioned case, the outcrop elevations would appear below and above the topographic profile line, respectively. However, it is the overall trend of the points that is the most significant and useful data and not necessarily their exact relationship to the topographic profile.

3. Results
[12] The olivine-enriched outcrops identified in this study extend over \( \sim 1100 \) km near the eastern end of Valles Marineris in Ganges and Eos Chasma. They are exposed up to 200 m above the canyon floor and typically \( \sim 3.5-4 \) km below the rim of the canyon, often forming linear arrangements parallel to the canyon walls in addition to large (often \( \geq 200 \) km²) flat-lying benches. Most outcrops have elevated thermal inertia compared to the surrounding canyon floor indicating they are composed of more consolidated, rocky material than mobile aeolian sediment. Through the use of MOLA elevation data and THEMIS and TES compositional data, we obtained three-dimensional information on the spatial distribution of these outcrops. The regional THEMIS mosaic (Figure 1a) shows the full extent of the olivine-enriched basalt unit. To the southwest of the study area (\( \sim 100 \) km) additional olivine-enriched material has been identified associated with impact crater ejecta. These materials were not included in this study as they are not in place material and their relationship to the primary outcrops identified is uncertain. However, this excavated material may indicate that the primary olivine-enriched unit identified in this study is more extensive than...
Figure 3. Three cross sections (A–A′′, B–B′, and C–C′) illustrate the relief between outcrops. (a) A–A′′ illustrates the relationship between the canyon floor and the outcrops, showing that olivine-enriched outcrops are always elevated above the canyon floor. (b) B–B′ illustrates that these outcrops persist through topographically high areas and appear in predictable locations. This cross section also illustrates the north-dipping trend of the outcrops. (c) C–C′ also illustrates the north-dipping trend of the outcrops and shows that these outcrops persist through topographically high areas. (d) MOLA topographic elevation data at 128 pixels per degree for the entire study region (2.5°N–12.5°S and 313–331.5°E). The locations of outcrops are plotted as white circles, while the locations for cross sections and topographic profiles are plotted as solid white lines. Dashed white lines illustrate the maximum lateral distance from the topographic profile line from which outcrop elevation points were collected.
mapped. As dust cover increases to the north and west of Ganges and Eos Chasma, the full extent of this unit may be unmappable as the homogenous dust easily obscures the underlying bedrock composition in the thermal infrared wavelengths [e.g., Ruff and Christensen, 2002] and the overlying plateau provides few windows to the depth of these outcrops. Therefore these units may continue further than mapped in this study.

[13] The composition of five outcrops was verified using TES spectral ratios following the method described by Christensen et al. [2003]. An example of our TES analysis is shown in Figure 4, where an outcrop centered at 0.2°S, 321.8°E (identified by the northernmost arrow in Figure 1),
approximately 450 km from the outcrop initially studied by Christensen et al. [2003] (identified by the southernmost arrow in Figure 1) is compared to the spectral ratio from Christensen et al. [2003] and a laboratory spectrum of olivine with a composition Fo68. The outcrop analyzed with TES data by Christensen et al. [2003] occurs in central Ganges Chasma whereas the outcrop chosen for this study occurs outside the main canyon, (Figure 1) near Ravi Vallis, allowing for constraints on changes in the olivine composition and abundance of these outcrops to be made.

Although ~80 instances of olivine-enriched material have been identified, the elevations of the ~60 most prominent outcrops have been determined using the combination of MOLA elevation data and THEMIS compositional data. The remaining ~20 instances were not mapped because of several limiting factors including: the limited areal extent of a particular outcrop, thermal inertia values indicative of a surface dominated by unconsolidated material, an association with a landform not likely a natural outcropping of bedrock (e.g., mass wasted material) and poor data quality (e.g., low surface temperature, poor image calibration due to factors such as long duration between image acquisition and shutter closing calibration images, etc). Typically, olivine-enriched outcrops are exposed in small hills or slightly raised areas that occur near the sides of the canyons, as well as in the walls of the canyon. They commonly occur in a linear arrangement with small (generally <5–10 km in length), repeated, and elongated outcrops occurring parallel to the direction of the canyon walls. Groupings of these small outcrops generally range from several km up to 50 km and more in length. However, the unit does not always crop out in a linear fashion, as seen in Figures 1b and 1c where the unit forms large flat benches.

This unit also crops out in a side canyon in the north of Figure 1 as a larger bench. These benches range in size from ~50 to ~800 km² and have elevated thermal inertias (>600 JK⁻¹ m⁻² s⁻¹/²), indicating that they are in place outcrops of olivine-enriched material and not the result of some mobilization mechanism (e.g., aeolian, mass wasting). There are no examples of the unit cropping out further up in the canyon walls, but there are several possibilities for why other layers are not seen elsewhere, including limited spatial resolution available on the slopes of cliffs, where they may be present but not visible or they may not be present at all.

High-resolution imagery from the Mars Orbiter Camera (MOC) [Malin et al., 1998] and the High-Resolution Imaging Science Experiment (HiRISE) [McEwen et al., 2007] help illustrate small-scale morphologies and albedo differences associated with these outcrops; however, Figures 1b and 1c are some of the only areas covered with high-resolution data (~1.5 m/pixel and ~0.5 m/pixel, respectively) at this time, making it difficult to ascertain the small-scale morphologies and associated features for many of the outcrop locations. The available images (Figures 5 and 6a) show that the olivine-enriched outcrops have a higher albedo than the smoother surrounding canyon floor and filled depressions (Figure 5). TES albedo values for Ganges and Eos Chasma are typically ~0.13, indicating little dust cover throughout the region [Christensen et al., 2001]. MOC and HiRISE visible imagery (Figures 5 and 6a) show that the olivine-enriched material has a fairly rough and pitted surface while the olivine-poor material has a mantled and smoother appearance. These morphologic characteristics are similar to those reported for other olivine-enriched terrains, including those...
was determined to be Christensen et al. primary outcrop investigated by evidence of dune forms. and seems to be dominated by aeolian material, as olivine-poor material has a smooth appearance, while the olivine-poor material has a smooth appearance and is largely unmantled with lower-albedo enriched material has an albedo of outcrops and the canyon floor (see Figure 1). The olivine-enriched outcrops that have been infilled with some amount of aeolian materials (identified by dune forms) that infill some of the depressions in the exposed rock. These lower inertia materials would have the effect of lowering the overall thermal inertia as the thermal inertia data from a single THEMIS pixel is integrated over 10,000 m\(^2\) [e.g., Fergason et al., 2006]. This relatively high thermal inertia, along with the rocky and unmantled morphologies observed in high-resolution imagery, indicate that this is an in place unit, which has been modified (e.g., aeolian processes, impact cratering, mass wasting) but is not a mobile aeolian material.

[17] Although the olivine-enriched outcrops in this study have a variety of thermal inertia values that are high (often times >600 JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\)), they are not necessarily consistent with a thermal inertia of unmantled bedrock (\(\approx 1200\) JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\)) as defined by Edwards et al. [2005]. However, upon examination of these occurrences with high-resolution imagery, which display a rough, pitted surface, we conclude that these outcrops are in place, exposed rock. The explanation for this discrepancy between the morphologic observations and the calculated thermal inertias, comes from the aforementioned aeolian materials (identified by dune forms) that infill some of the depressions in the exposed rock. These lower inertia materials would have the effect of lowering the overall thermal inertia in this study, thermal inertia was calculated for individual THEMIS nighttime temperature images (to assess image quality and calibration) [Fergason et al., 2006] that covered several of the outcrops under investigation, including Figures 1b and 1c. Many of the outcrops in question have a much higher thermal inertia than the surrounding floor material, typically ranging from \(\approx 400\) to \(\approx 600\) JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\), with several outcrops having thermal inertia values of greater than \(\approx 600\) JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\), sometimes reaching thermal model limits of 1400 JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\).

[18] Through the use of MOLA single point elevation data and gridded data, the minimum outcrop thicknesses are estimated to range from \(\approx 60\) to \(\approx 220\) m, with an average value of \(\approx 150\) m. Additionally, by plotting the average outcrop elevation data and spatial data together, it is possible to determine the continuity, orientation, dip, and extent of the olivine bedrock outcrops (Figure 3). The uppermost surfaces of individual outcrops typically occur within \(\approx 200\) m of the canyon floor, often forming small hills or benches in the canyon. Cross section A-A”, which was constructed along the main canyon system floor (Figure 3a), illustrates that the topographic profile of the canyon floor, depicted as a solid line, is nearly always lower than the points of average elevation for each of the outcrops. Other cross sections (B–B’ and C–C’, Figures 3b and 3c) display a similar trend, where the olivine-enriched unit persists between topographically high areas and appears only at a restricted range of elevations in or near the walls of the canyon.

[19] MOLA elevation and THEMIS multispectral data indicate that these olivine-enriched outcrops are not just located at similar elevations near the bottom of Ganges and

Figure 5. MOC image R0802721 (centered near 325.5°E, 3°S) covers the contact between the olivine-enriched outcrops and the canyon floor (see Figure 1). The olivine-enriched material has an albedo of \(\approx 0.14\), a rough, pitted appearance, and is largely unmantled with lower-albedo aeolian materials infilling small pits and craters (see arrow), while the olivine-poor material has a smooth appearance and seems to be dominated by aeolian material, as evidenced by dune forms.

found in Ares Vallis [Rogers et al., 2005], Gusev Crater [Ruff et al., 2007], Isidis Planitia [Tornabene et al., 2008], and Nili Fossae [Hamilton and Christensen, 2005; Mustard et al., 2007], (Figures 6b–6e, respectively). In addition to this morphologic difference, the olivine-enriched material in Ganges and Eos Chasma is elevated above the surrounding floor material, which have a thermal inertia and morphology (dune forms are observed throughout the area in high-resolution imagery) consistent with aeolian materials. However, there are areas in the olivine-enriched outcrops that have been infilled with some amount of aeolian material, identified by small-scale dunes in many small pits and hollows.

[16] Additionally, we have characterized the physical nature of the outcrops using thermal inertia. Christensen et al. [2003] note that olivine-enriched outcrops have a high nighttime temperature when compared to the surrounding canyon floor (\(\approx 10\) K higher). The thermal inertia of the primary outcrop investigated by Christensen et al. [2003] was determined to be \(\approx 700\) JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\) [Christensen et al., 2003], which is a thermal inertia value near that of rock and is significantly higher than thermal inertia values for unconsolidated material. While this thermal inertia is not consistent with completely unmantled bedrock, this value is likely lowered because of subpixel mixing with lower inertia aeolian materials (\(\approx 250–300\) JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\) [e.g., Putzig et al., 2005; Fergason et al., 2006]) present in hollows and pits observed on the outcrops (Figure 5). In this study, thermal inertia was calculated for individual THEMIS nighttime temperature images (to assess image quality and calibration) [Fergason et al., 2006] that covered several of the outcrops under investigation, including Figures 1b and 1c. Many of the outcrops in question have a much higher thermal inertia than the surrounding floor material, typically ranging from \(\approx 400\) to \(\approx 600\) JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\), with several outcrops having thermal inertia values of greater than \(\approx 600\) JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\), sometimes reaching thermal model limits of 1400 JK\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\).
Eos Chasma, but they form a contiguous, rocky layer that is visible between topographically high areas and outcrops at consistent locations in the canyon system. In addition, this layer is relatively thin (typically < 200 m) when compared to the 4.5 km of overlying materials.

If these outcrops are, in fact, representative of a large contiguous layer, calculating the layer’s dip angle and dip azimuth could help constrain both the emplacement mechanism and the amount of crustal deformation the area has undergone. For example, elevation variations may be explained by volcanic fallout [e.g., Wilson and Head, 1994; Wilson and Head, 2007] if the layer appears to drape preexisting topography or the unit may be offset because of the regional tectonic environment [e.g., Phillips et al., 2001]. Cross sections B–B’ and C–C’ (Figures 3b and 3c) were specifically chosen to illustrate the dip angle and azimuth of this layer, in addition to the continuity and extent of the unit. Through the analysis of these cross sections, we find that the layer dips slightly to the northeast. By using the best linear fit to the A–A’ (Figure 3a) data, the dip angle was measured at ~0.013 ± 0.004° (95% confidence interval) to the northeast, which is essentially flat lying when compared to the large extent of this unit. The topographic profile line A–A’ (Figure 3a) indicates that the canyon floor was measured to dip to the northeast, with a dip angle of ~0.045 ± 0.001° and an azimuth consistent with the outcrops. These measured dips also correspond with the large-scale MOLA topography where the highest location in this scene occurs in the southwest corner and the lowest occurs in the northeast section. However, the plateau was measured to dip at a noticeably higher angle (~0.293 ± 0.005°) but in a similar azimuth to the canyon floor and the olivine-enriched outcrops. The differential dip between the plateau surface and the olivine layer suggests that several regional tectonic events have affected the stratigraphic column or deposition of the olivine-rich layer may have occurred on an inclined surface.

In addition to the regional tilt of this layer, there are small-scale variations (~200 m) in the data but these variations are small when compared to the overall extent of the layer (>1100 km) thus, this layer is relatively flat lying over large distances. These relatively small variations indicate that any vertical offset of this layer was minimal. The linear arrangement of many outcrops helps affirm that the unit is a continuous layer within the canyon walls. The outcrops that occur outside of the main canyon system (e.g., the outcrop near Ravi Vallis, used as the example location for the TES spectral analysis discussed earlier and the small craters with olivine-enriched ejecta to the southwest of the study area) suggest a more extensive, continuous layer that persists underneath topographically high areas such as the overlying plateau between Ganges Chasma and Ravi Vallis and only outcrops at specific predictable elevations (e.g., Figures 3b and 3c). For instance, the lowest elevation in the southernmost area of Shalbatana Vallis (1°N, 315°E) is higher than the expected outcrop elevation and is consistent with the lack of an olivine-enriched unit in this canyon.

Figure 6. HiRISE imagery of a variety of olivine-enriched units identified on Mars [e.g., Hamilton and Christensen, 2005; Rogers et al., 2005; Mustard et al., 2007; Ruff et al., 2007; Tornabene et al., 2008]. All images are displayed at the same scale (~56 cm/pixel) for easy morphologic comparison between areas. Olivine-enriched material in (a) Eos Chasma (HiRISE image PSP_001798_1685, centered near 322°E, 10°S), (b) Ares Vallis (HiRISE image PSP_004118_1865, centered near 341°E, 6.5°N), (c) Gusev Crater (HiRISE image PSP_002133_1650, centered near 175.5°E, 14.5°S), (d) Isidis Basin (HiRISE image PSP_002756_1830, centered near 85°E, 3°N), and (e) Nili Fossae (HiRISE image PSP_001754_2020, centered near 78°E, 22°N). All localities exhibit the rough, pitted texture observed in Ganges and Eos chasmas (Figure 6a) but the scale of these textures is variable, where Ares Vallis (Figure 6b) and Nili Fossae (Figure 6e) exhibit smaller-scale features and Gusev Crater (Figure 6c) and Isidis Basin (Figure 6d) exhibit larger-scale features than the Ganges and Eos chasmas unit.
However, it is not possible to determine if this location is a western limit on the extent of the unit because the unit may be present in the subsurface.

[22] Although most olivine-enriched outcrops occur near the walls of the canyon and have morphologies and thermal inertias consistent with in place, rocky materials, we have observed some evidence of transport as well. Olivine-enriched material has been carried as debris into the canyon floor by mass wasting, which can be seen in two locations in Figure 1a near the western edge of Ganges Chasma (318.7°E, 8.2°S; 315.5°E, 8.4°S, Figure 7). Although aeolian materials are observed in high-resolution imagery, they do not have a spectral signature consistent with a relative enrichment in olivine. It is not likely that aeolian materials are the primary source for this unit, rather aeolian processes only aid in eroding the outcrop and allow for transportation of these eroded materials over small distances.

4. Discussion

[23] The identification and mapping of this regionally extensive unit poses some interesting questions as to the volume of material it represents, relationship to other olivine-enriched basalts in the area and globally, and its geologic origin.

4.1. Volume

[24] Assuming that the maximum extent of the unit corresponds to the maximum extent of the observed outcrops, an estimate of the minimum volume of olivine-enriched material can be calculated by fitting an ellipse to a region enclosing all of the identified outcrops. The area of the ellipse of maximum extent is $\approx 6.6 \times 10^5$ km$^2$. Using the average thickness of 150 m, a volume of $\approx 9.9 \times 10^4$ km$^3$ has been estimated. In addition to the uncertainty in the thickness estimated for this layer, the calculated volume is considered a minimum estimate since the layer may continue further under the plateau where it cannot be observed. Additionally, small craters in the floor of Eos Chasma, to the southwest of the study area, appear to excavate olivine-enriched material from below the surface and indicate that this layer likely continues further than the mapped outcrops. The full extent of this unit is also likely unknown because of increasing dust cover to the north and west of Ganges and Eos Chasma, obscuring the underlying bedrock composition, further emphasizing that the volume estimate stated above is a minimum value.

[25] Large igneous provinces on Earth, for example the Siberian Traps or the Deccan Traps, have total magma emplacement volumes of $1 \times 10^6$ km$^3$ [Officer et al., 1987] to $4 \times 10^6$ km$^3$ [Courtillot et al., 1999] and $2 \times 10^6$ km$^3$ [Widdowson et al., 1997] to $4 \times 10^6$ km$^3$ [Courtillot et al., 1999], respectively. All of these volumes are more than an order of magnitude larger than the estimated volume of the Ganges and Eos Chasma unit. These terrestrial cases represent the total volume of magma erupted, which consist of many different units erupted over long time periods (e.g., $\approx 0.9 \pm 0.8$ Ma for the Siberian Traps [Campbell et al., 1992]). The Ganges and Eos Chasma case is a single unit likely composed of several different eruptive events within what has been interpreted as a massive sequence of lava flows exposed in the canyon walls [McEwen et al., 1999]. This comparison to large igneous provinces on Earth illustrates that the size of this Martian unit is not unique for other planetary bodies in the solar system. Additionally, if the Ganges and Eos Chasma olivine-enriched basalts are only a single unit, corresponding to a distinct period in Martian history, the volume estimates for this unit are consistent with what may be expected for a single unit in large igneous provinces on Earth.

4.2. Comparison to Other Olivine Basalts

[26] By comparing an example TES spectral ratio from this work and the ratio performed by Christensen et al. [2003] to several laboratory-measured olivine spectra [Salisbury et al., 1992; Christensen et al., 2000; Koeppen and Hamilton, 2008], we illustrate that both spectral ratios are a good match to the three main absorption features of olivine (Figure 4). However, an important property of olivine is that higher-wavelength spectral features systematically shift to either shorter or longer wavelengths as a function of Mg and Fe content of the olivine [Salisbury et al., 1992; Hamilton et al., 1997; Koeppen and Hamilton, 2008]. This is typically represented by forsterite content (Fo$_{\text{ext}}$, the Mg-rich end-member of the solid solution series) defined as (Mg/(Mg + Fe)). This systematic shift makes it possible to estimate the forsterite content of this specific olivine unit. A forsterite content of $\approx 0.68$ (Fo$_{68}$) proved to be the best match of all the laboratory olivine spectra examined (with major at absorptions at $\approx 10.6$, $\approx 19.0$, and $\approx 23.5$ $\mu$m) for both the ratios performed in this work and the ratio performed by Christensen et al. [2003]. However, there is a small shift in some of the shorter-wavelength absorption features for both TES spectral ratios, indicating that this Fo$_{68}$ is not a perfect match and may be slightly higher or lower than Fo$_{68}$. Not only is this unit olivine-enriched but the composition of the olivine remains relatively constant over large distances, as the ratio in this study and the Christensen et al. [2003] example ratio match each other well despite being separated by over $\approx 450$ km. Koeppen and Hamilton [2008]
have created global maps utilizing TES spectral data illustrating the distribution of olivine for a variety of Fo compositions. Koeppen and Hamilton [2008] found that the best match for Ganges and Eos Chasma is the olivine index that corresponds to Fo58–74. These data further strengthen the argument that this is a single, extensive compositionally uniform unit and is not composed of several smaller olivine-enriched members of differing composition, as no layering is observed in high-resolution MOC or HiRISE imagery. However, distinguishing detailed compositional information is limited to the scale of a single TES pixel (3 × ~6 km), as subpixel mixing of material with different forsterite content may be present but not resolvable by TES or distinguishable by the lower spectral resolution data available from THEMIS.

[27] McSween et al. [2006] have identified picritic olivine basalts in Gusev in individual samples examined by instruments on the Mars Exploration Rovers, including Panoramic Camera (PanCam) [Bell et al., 2006], Miniature Thermal Emission Spectrometer (Mini-TES) [Christensen et al., 2004], Mössbauer Spectrometer [Morris et al., 2004] and Alpha Particle X-ray Spectrometer [Gellert et al., 2004; Gellert et al., 2006]. It is likely that these basalts are derived from more primitive, less fractionated magmas. The proportion of the olivine described by McSween et al. [2006] and Koeppen and Hamilton [2008] on Mars ranges from 0% abundance for large sections of the planet to an extreme of 20–30% abundance, indicating that the olivine basalts identified in this study (with an abundance of ~10 to >15%) have higher than typical olivine content on Mars when viewed from orbit. Although the rocks at Gusev crater do not occur in the primary region where olivine is found on Mars, Eos and Ganges Chasma are located in one of the areas where higher olivine concentrations are commonly found [Koeppen and Hamilton, 2008]. In addition, Koeppen and Hamilton [2008] have found that the forsterite composition of olivine on Mars can vary dramatically with olivine of Fo45 occurring in small occurrences near Argyre and Hellas basins and widespread occurrences of a more intermediate forsterite content (e.g., Fo70–40), consistent with what is observed in Ganges and Eos Chasma. However, no confident occurrences of olivine with <Fo30 were identified, because of large inaccuracies in the spectral index used caused primarily by atmospheric contributions [Koeppen and Hamilton, 2008].

[28] Abundant olivine rich rocks are also found near the Columbia Hills in Gusev Crater. Ruff et al. [2007] identified an olivine-enriched terrain utilizing the Mini-TES, which has been described as “Rubble Terrain” due to the appearance in PanCam and HiRISE images. Large rounded boulders and knobs of rubbly, layered, olivine-enriched materials have led Ruff et al. [2007] to hypothesize that this may be a volcaniclastic deposit. However, an alternate possibility is that these materials are impact-derived deposits similar to those suggested for the Nili Fossae region originating from the Isidis Basin impact event [Mustard et al., 2007; Tornabene et al., 2008]. The terrain identified also has an elevated nighttime temperature [Ruff et al., 2007] implying a rockier material. When viewed using high-resolution imagery, there are significant morphological similarities between the Gusev crater “Rubble Terrain” and the unit under investigation in this study. Figure 6a illustrates this similarity as the olivine-enriched terrain has a rough and pitted texture similar to that described by Ruff et al. [2007] (Figure 6c).

[29] Another example location where an olivine (Fo60) basalt has been identified utilizing TES and THEMIS data is Ares Valles [Rogers et al., 2005]. The outcrop of olivine in this location has a relatively high thermal inertia (575–840 JK−1 m−2 s−1/2) and appears to occur in two primary layers. Rogers et al. [2005] conclude that the emplacement mechanism for this olivine-bearing unit (with an olivine abundance of >15%) could be explained by an intrusive and/or extrusive event. There are several similarities with the olivine basalts identified in this study including the relatively high thermal inertia, morphologic evidence, olivine forsterite content and the olivine abundance of >15% which all agree well with the olivine basalt identified in this study. In addition to these similarities, both deposits are relatively close to each other, separated by ~600 km and occur at roughly similar elevations, giving rise to the possibility that the emplacement of these two units may be related.

[30] The region around the Nili Fossae is another location where olivine-enriched material has been identified [Hamilton and Christensen, 2005; Mustard et al., 2005; Mustard et al., 2007] utilizing THEMIS, TES, and Observatoire pour la Minéralogie, l’Eau, les Glaces, et l’Activité (OMEGA) spectral data. This deposit is to the northeast of the Syrtis Major volcanic shield, and contains a ~30,000 km² contiguous olivine-enriched outcrop. This deposit is associated with concentric fractures that may be related to the Isidis basin impact event. This olivine-enriched locality has similar characteristics to those identified in this study where outcrops of this unit have a rough and pitted appearance and appear to be largely free of aeolian material. However, sand dunes are prevalent in this area and appear to overly a hard substrate of olivine-enriched material. Hamilton and Christensen [2005] have determined that the composition of the olivine in this location is ~Fo68–75 and often has elevated thermal inertias (~455 JK−1 m−2 s−1/2) when compared to the olivine-poor materials. Additionally, this olivine-enriched unit displays similar characteristics to what is observed in southwest Isidis basin [Tornabene et al., 2008], where an olivine-enriched unit has been mapped and characterized using compositional, thermophysical and morphologic data.

[31] Morphologies associated with the olivine-enriched materials found in Nili Fossae generally agree with those in Ganges and Eos Chasma, with the exception of the curved lineaments identified by Hamilton and Christensen [2005]. These lineaments are associated with flat-lying layering in Nili Fossae, which has not been observed in the Ganges and Eos Chasma unit. However, when this area was characterized using OMEGA and HiRISE [Mustard et al., 2007], these lineaments appear to be related to the underlying phyllosilicate material in the region, which predates the overlying olivine-enriched unit. Mustard et al. [2007] propose that this olivine-enriched material represents an impact melt deposit related to the Isidis Basin formation event. As no lineaments have been observed in or near the Ganges and Eos Chasma olivine-enriched unit, this indicates that there are no correlated layered phyllosilicate
materials present in this location, unlike those found in Nili Fossae [Mustard et al., 2007]. Alternatively, Tornabene et al. [2008] have proposed that the underlying phyllosilicate-rich terrain identified in Nili Fossae is more likely representative of ejecta associated with the Isidis Basin impact event. If this interpretation is correct, it is also consistent with the lack of these features in Ganges and Eos Chasma, as there are no clear large impact basins within 1000s of km of these localities. Additionally this result is supported directly by OMEGA data, which did not identify phyllosilicate materials in Ganges and Eos Chasma [Bibring et al., 2006].

[32] The Ares Vallis olivine-enriched bedrock [Rogers et al., 2005] displays the most similarities to the Ganges and Eos Chasma unit where olivine abundances, composition, morphology and thermal inertia correlate best. In addition, this site is relatively close (600 km) to the Ganges and Eos Chasma unit and crops out at a similar elevation, which may indicate even more widespread olivine-enriched basaltic volcanism than hypothesized in this study. However, of specific note are the striking similarities (e.g., olivine abundance, forsterite content, thermal inertia data, morphologies) between all of the previously discussed olivine-enriched units, which are spread out over large distances on the surface [e.g., Hamilton and Christensen, 2005; Rogers et al., 2005; Mustard et al., 2007; Ruff et al., 2007; Tornabene et al., 2008] and the Ganges and Eos Chasma layer. Figure 6 highlights the morphologic similarities (especially rough, pitted textures) of these units, with HRSC imagery shown for several sites where olivine-enriched units have been identified. However, the scale of the identified textures is variable, with Ares Vallis (Figure 6b) and Nili Fossae (Figure 6e) exhibiting smaller-scale features and Gusev Crater (Figure 6c) and Isidis Basin (Figure 6d) exhibiting larger-scale features than the Ganges and Eos Chasma unit (Figure 6a). This variability may be due to different weathering conditions or differences in regional histories. Additionally, Nili Fossae shows significantly more aeolian dune forms than other areas, indicating that this area may be subject to more gradational processes or is composed of more friable material than other areas.

[33] Most in place olivine-enriched units have olivine abundances which are typically >15% and have intermediate forsterite content (~0.68). Additionally, these units typically have elevated thermal inertia (>500 KJ m^-2 s^-1/2), which are not necessarily consistent with unaltered bedrock, but are likely lowered because of finer-grained aeolian materials commonly observed in hollows on these surfaces or the presence of an olivine lag eroded from a cap unit [Christensen et al., 2005; Mustard et al., 2007; Tornabene et al., 2008]. In addition to these localized regional examples, Koeppen and Hamilton [2008] indicate that olivine with a forsterite content of ~0.68 are most common in the southern highlands, which is consistent with the findings in this study. Several Martian meteorite samples (e.g., Chassagny and ALH 77005), which are olivine-rich also, have the best spectral matches with Fo68 [Hamilton et al., 2003] further strengthening the argument that olivine-bearing materials with this forsterite content are common on Mars. Compositions and olivine abundance are similar for many examples of in situ olivine on Mars, and when considering unit age, most olivine-enriched units (including the Ganges and Eos Chasma layer) were likely emplaced during the Noachian [e.g., Rogers et al., 2005; Mustard et al., 2007; Tornabene et al., 2008], early in Martian history. Additionally, it is likely that when Martian meteorites (e.g., the Nahklites and Chassignites, with crystallization ages of ~1.3 Gyrs [Nyquist et al., 2001]) were ejected from the surface, they sampled lower stratigraphy (where olivine-enriched units with this forsterite content appear to be more common), which is also consistent with what is observed in Ganges and Eos Chasma.

4.3. Geologic Origin of the Unit

[34] There are several geologic processes that could produce a layer such as that observed in this study, including (1) an intrusive mafic sill, (2) volcanism associated with tectonic rifting of the Valles Marineris system, (3) a volcaniclastic flow deposit, or (4) a discrete episode in Martian history during which flood lavas were erupted onto the surface. Emplacement as a sill can explain the contrasting composition of the unit relative to regional material. The source for the sill may have been derived from more primitive magmas than the igneous units that are presumed to comprise the regional material, which show no olivine enrichment indicative of primitive magmas. However, we do not favor this explanation, primarily because of the large lateral extent of the unit. On Earth some of the largest sills extend for thousands of square kilometers [e.g., Francis, 1982; Kavanagh et al., 2006], significantly smaller than the Ganges and Eos Chasma unit, which has an areal extent of ~6.6 × 10^5 km^2. Additionally, on Earth, large sills are commonly associated with crustal thinning and continental breakup [e.g., Francis, 1982]. Evidence that further strengthen this argument is the lack of any feeder dike structures in high-resolution imagery and the absence of any thermally metamorphosed materials commonly associated with intrusive events (e.g., clays from hydrothermal alteration) [Bibring et al., 2005]. Rifting and crustal thinning associated with the formation of Valles Marineris provide another possibility for the formation of this unit. Extension associated volcanism (usually basic) typically occurs in the final stages of rifting where the canyon is already opened allowing lavas to spread onto the preexisting canyon floor. If the unit was emplaced via this mechanism, olivine-enriched basalts would occur primarily on the floor of the canyon and not in the walls, as observed. An extensive episode of flood lava eruptions or volcaniclastic flows deposited on the surface in a relatively short time period could explain the distribution of outcrops observed in the canyon system, the estimated volume of material erupted, and composition. In this case, these flows have likely been buried under a large sequence of other flows [McEwen et al., 1999]. This hypothesis can effectively explain the small variations in outcrop elevations and the seemingly single layered nature of the unit.

[35] Variations in elevation of this unit (seen in Figures 3b–3d) are relatively small when compared to the lateral extent of this unit; however, this layer does not appear to lie on a perfect plane requiring some other explanation for the observed variations. If a series of flood lavas or a volcaniclastic deposit were the source of this unit, variations in the average elevation data can be explained by flows filling or draping preexisting features such as canyons, grabens, or
craters. If the unit was emplaced by an intrusive mechanism, the observed irregularities can be attributed to magma preferentially following weaknesses in the country rock. Tectonic activity [Phillips et al., 2001], such as faulting observed in the Valles Marineris region by previous studies [e.g., Watters and Maxwell, 1983; Mège and Masson, 1996; Peulvast et al., 2001; Wilkins and Schultz, 2003] may have also occurred, providing another possible explanation for the observed elevation variations; however, no direct evidence for faults has been observed in this study.

[36] Characterizing the magma evolution of a relatively thin olivine-enriched lava flow or volcaniclastic deposit depends largely on the nature of the olivine in the material. Olivine included as phenocrysts versus xenocrysts (foreign crystals incorporated into the magma) or magma chamber cumulate materials likely have different parent magmas, describe different crystallization sequences, and have different petrogenic histories [McSween et al., 2006]. Magma with olivine included as cumulates or xenocrysts may have undergone more fractional crystallization than magma with primary olivine phenocrysts. High-pressure experiments [Bertka and Holloway, 1994] have placed constraints on the stable mineral phases at depth, indicating that the Martian mantle is likely composed of olivine, orthopyroxene, and spinel at ~75 km below the surface. If we consider an eruption direct from the Martian mantle, then to retain much of this primary phase assemblage, little fractional crystallization, little to no assimilation of evolved materials and low degrees of partial melting (all lowering the overall olivine fraction of the magma) must have occurred to form the olivine-enriched basalts found in Ganges and Eos Chasma. Although other minerals associated with this assemblage (orthopyroxene and spinel) are not directly detected in this work, evidence for orthopyroxene in this area has been noted by several earlier studies [e.g., Bandfield, 2002; Hamilton et al., 2003; Birbring et al., 2005; Rogers and Christensen, 2007]. If the olivine is included as primary phenocrysts, then it is likely that these are primitive magmas that were erupted on the surface as picritic basalts, providing additional evidence that the Martian mantle is likely undepleted with respect to iron content [e.g., McSween, 1994]. This is assuming that the formation of the olivine is a primary process and the magma was not significantly modified to include olivine cumulate materials or xenocrysts. However, the most likely scenario is that these basalts represent primitive magmas, as suggested for the Gusev Crater olivine basalts [McSween et al., 2006]. Unfortunately, it is difficult to distinguish the inclusion style of olivine utilizing ground-based measurements onboard the Mars Exploration Rovers [McSween et al., 2006], making them even less distinguishable from the orbital data available in this study.

[37] If these are lava flows, then potential eruptive centers must be considered. However, there are no evident sources for these flows, but on Earth and the Moon the source vents for flows are typically buried and the small areas exposed in the Martian unit make the detection of source vents unlikely. One possibility is that these flows may be related to the initiation of Tharsis volcanism, yet not necessarily associated with any of the landforms observed today. If this were the case, these flows would likely be some of the first lavas erupted which were subsequently buried by more evolved and fractionated, olivine-depleted lavas, that obscured the source vent or caldera. A similar hypothesis has been formed for Syrtis Major and the Isidis Basin region, where Noachian to Hesperian picritic lavas were erupted in the early stages of volcanism at Syrtis major [Tornabene et al., 2008]. Tornabene et al. [2008] do not identify stratigraphically higher flows indicating that the formation of picritic lavas did not occur again in the history of Syrtis Major. The observed terrain may then be interpreted as heavily impacted ancient terrain, which has been more recently exposed. Additionally, this is a plausible scenario for the Ganges and Eos Chasma picritic flows, which likely occurred during a discrete time early in Martian history (early to middle Noachian), as flows are not observed higher in the stratigraphic section, most outcrops occur near the same elevation (low in the canyon stratigraphy) and all outcrops are relatively thin when compared to the overlying stratigraphy [McEwen et al., 1999].

[38] The exact timing of this event cannot be determined as observations of a nadir-pointing THEMIS instrument are limited on the steep slopes of the canyon walls. There may be more events of a similar composition emplaced throughout Martian history captured in the walls of the canyon but they may not be able to be imaged by nadir-pointing THEMIS observation. If more events occurred throughout Martian history in this location, bench-forming morphologies similar to those observed for the identified unit would be expected to occur at a variety of locations in the canyon walls; however, this is not observed supporting the conclusion that the layer identified in this study is the largest occurrence of olivine enrichment noted to date.

5. Conclusions

[39] Our conclusions are as follows:

[40] 1. We have identified an in situ, olivine-enriched stratigraphic layer, which extends laterally over a distance of >1100 km and has a minimum volume of ~9.9 × 10⁶ km³. Additionally, olivine-enriched material outside the primary study area has been observed as ejecta from small craters in the canyon floor, giving rise to the possibility that this layer is even larger than estimates given here. This layer was characterized and identified utilizing TES hyperspectral data and THEMIS multispectral images, along with THEMIS nighttime temperature data to determine the thermophysical properties of the outcrops. Most outcrops have elevated thermal inertia values (often >600 JK⁻¹ m⁻² s⁻¹/², with extremes of >1200 JK⁻¹ m⁻² s⁻¹/²), which indicates that this unit is not a mobile sediment and is an in place rocky unit. These observations agree well with morphologic evidence from high-resolution imagery, which display a relatively unmannetled, rough and pitted surface associated with the olivine-enriched material, with some aeolian bed forms infilling the hollows and pits of the surface observed by HiRISE and MOC imagery (Figure 5).

[41] 2. In addition to infrared data, we also used MOLA elevation data to constrain the vertical dimension of this layer, allowing for the continuity, extent, dip and orientation to be constrained. This layer is continuous over >1100 km and the olivine-enriched outcrops seem to define a layer that is essentially flat lying. This unit persists underneath topo-
graphically high areas appearing only in expected, elevation-dependent locations, and is one of the largest continuous compositional units found on Mars to date with an estimated volume of \(9.9 \times 10^6 \text{ km}^3\).

3. Four possibilities for the geologic origin of the olivine-enriched unit include (1) volcanism associated with tectonic rifting of the Valles Marineris system, (2) a volcaniclastic flow deposit, (3) an intrusive mafic sill, or (4) a discrete episode in Martian history during which flood lavas were erupted onto the surface. The most likely explanation for the geologic origin of this layer is an eruptive event consisting of compositionally uniform olivine-enriched flood lavas originating from a primitive mantle source region.

4. When the Ganges and Eos Chasma unit is compared to other olivine-enriched units on Mars, namely those identified in Ares Vallis [Rogers et al., 2005], Gusev Crater [Ruff et al., 2007], Isidis Planitia [Mustard et al., 2007; Tornabene et al., 2008], and Nili Fossae [Hamilton and Christensen, 2005], striking compositional (>15% olivine abundance and \(\sim F_{Ol}\)), morphologic (commonly rough, pitted textures) and thermophysical (typically >500 J K\(^{-1}\) m\(^{-2}\) s\(^{-1/2}\)) similarities are observed. Additionally many of these units are hypothesized to have been emplaced early in Martian history. These similarities in age and characteristics lead to the possibility that there was a discrete period of time early in Mars history, when compositionally uniform and extensive olivine-enriched basalts were erupted onto the surface.

Acknowledgments. The authors thank Livio Tornabene and Keith Milam for reviews, which improved the manuscript. This work was funded by NASA 2001 Mars Odyssey THEMIS project.

References


Bibring, J.-P., et al. (2006), Global mineralogical and aqueous Mars history derived from OMEGA/Mars Express data, Science, 312(5772), 400–404, doi:10.1126/science.1122659.


C. S. Edwards and P. R. Christensen, Mars Space Flight Facility, School of Earth and Space Exploration, Arizona State University, P.O. Box 876305, Tempe, AZ 85287-6305, USA. (christopher.edwards@asu.edu)

V. E. Hamilton, Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, USA.