The Circum-Hellas Volcanic Province, Mars: Overview

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Abstract

Building on previous studies of volcanoes around the Hellas basin with new studies of imaging (High-Resolution Stereo Camera (HRSC), Thermal Emission Imaging System (THEMIS), Mars Orbiter Camera (MOC), High-Resolution Imaging Science Experiment (HiRISE), Context Imager (CTX)), multispectral (HRSC, Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité (OMEGA)), topographic (Mars Orbiter Laser Altimeter (MOLA)) and gravity data, we define a new Martian volcanic province as the Circum-Hellas Volcanic Province (CHVP). With an area of ~2.1 million km², it contains the six oldest central vent volcanoes on Mars, which formed after the Hellas impact basin, between 4.0 and 3.6 Ga. These volcanoes mark a transition from the flood volcanism that formed Malea Planum ~3.8 Ga, to localized edifice-building eruptions. The CHVP volcanoes have two general morphologies: (1) shield-like edifices (Tyrrhena, Hadriaca, and Amphitrites Paterae), and (2) caldera-like depressions surrounded by ridged plains (Peneus, Malea, and Pityusa Paterae). Positive gravity anomalies are found at Tyrrhena, Hadriaca, and Amphitrites, perhaps indicative of dense magma bodies below the surface. The lack of positive-relief edifices and weak gravity anomalies at Peneus, Malea, and Pityusa suggest a fundamental difference in their formation, styles of eruption, and/or compositions. The northernmost volcanoes, the ~3.7–3.9 Ga Tyrrhena and Hadriaca Paterae, have low slopes, well-channeled flanks, and smooth caldera floors (at tens of meters/pixel scale), indicative of volcanoes formed from poorly consolidated pyroclastic deposits that have been modified by fluvial and aeolian erosion and deposition. The ~3.6 Ga Amphitrites Patera also has a well-channeled flank, but it and the ~3.8 Ga Peneus Patera are dominated by scalloped and pitted terrain, pedestal and ejecta flow craters, and a general ‘softened’ appearance. This morphology is indicative not only of surface materials subjected to periglacial processes involving water ice, but also of a surface composed of easily eroded materials such as ash and dust. The southernmost volcanoes, the ~3.8 Ga Malea and Pityusa Paterae, have no channeled flanks, no scalloped and pitted terrain, lack the ‘softened’ appearance of their surfaces, but they do contain pedestal and ejecta flow craters and large, smooth, bright plateaus in their central depressions. This morphology is indicative of a surface with not only a high water ice content, but also a more consolidated material that is less susceptible to degradation (relative to the other four volcanoes). We suggest that Malea and Pityusa (and possibly Peneus) Paterae are Martian equivalents to Earth’s giant calderas (e.g., Yellowstone, Long Valley) that erupted large volumes of volcanic materials, and that Malea and Pityusa are probably composed of either lava flows or ignimbrites. HRSC and OMEGA spectral

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1. Introduction

More than half the surface of Mars is covered by volcanic deposits, including lava flows and inferred pyroclastic materials, reflecting volcanic activity that has spanned much of the known history of the planet (see reviews by Greeley and Spudis, 1981; Mouginis-Mark et al., 1992; Neukum et al., 2004a). In the early 1970s, the first successful Mars orbiter, Mariner 9, returned low-resolution images (1–3 km/pixel) that revealed the geological diversity of the surface, including the presence of features near the Hellas impact basin that appeared to be volcanoes (McCaulley et al., 1972; Carr, 1973; Carr et al., 1973; Potter, 1976; Peterson, 1977). These features had radial patterns of ridges and channels, hints of slightly circular craters, and relatively low topographic relief. The term patera was applied to these and similar features seen on Mars. In planetary nomenclature (http://planetnames.wr.usgs.gov/append5.jsp), patera refers to a shallow crater with a scalloped or complex edge (Strobell and Masursky, 1990). However, in planetary literature for Mars, the term also commonly refers to volcanic constructs (e.g., Carr, 1981). The term highland patera was applied to a category of low-profile volcanoes found mostly in the cratered highlands (Plescia and Saunders, 1979) and is also commonly used, especially for the features in the Hellas region.

As reviewed below, in the years following Mariner 9, geological mapping and many topical investigations were conducted for the paterae of the Hellas region, which can now be enhanced substantially by new and better data. Building on this body of work and the insight provided by the current Mars missions, we propose the formal designation of the Circum-Hellas Volcanic Province (CHVP), shown in Figs. 1a and b.

2. Background

In their geological analysis of the Mariner 9 data, McCaulley et al. (1972), Carr (1973), and Carr et al. (1973) recognized the volcanic origins of the features around the Hellas basin and summarized the volcanic history of Mars, with ages for these three paterae (later named Tyrrhena, Hadriaca, and Amphitrites) of 3.5–4.0 Ga, based on crater counts (Carr, 1976). As part of the systemic Mars geological mapping program (see also Scott and Carr, 1978), Potter (1976) analyzed the eastern part of the Hellas basin and Amphitrites Patera, and noted flow-like patterns that he suggested were produced by fluid lava flows. At about the same time, Peterson (1977) mapped the western part of the Hellas basin and identified many of the volcanic centers, later codified in his prescient paper (Peterson, 1978), in which he suggested that the paterae are centered on ring fractures associated with the Hellas impact structure (Fig. 1). Later studies by Frey et al. (1991) inferred four rings from a previously unrecognized basin (centered on what is now recognized as Pityusa Patera) with diameters of 600, 1200, 1700, and 2200–2400 km, but they admitted that some of the features noted as part of these rings could also apply to rings of the Hellas basin, as suggested by Peterson (1978). Peterson (1978) also noted the numerous mare-like ridges in the areas around the paterae, and suggested that these could be surface manifestations of feeder dikes. Because the paterae have low topographic relief, Peterson (1978) suggested that they are composed either of ultramafic lavas, which were erupted as very low-viscosity, fluid lavas, or as ash-flows, analogous to those of Earth’s Yellowstone volcanic region.

In the mid-1970s, the Viking orbiters began returning images substantially improved over those of Mariner 9, enabling refinements of the ideas proposed earlier (Carr et al., 1977a). For example, Greeley and Spudis (1981) suggested that Tyrrhena and Hadriaca Paterae are multistage volcanoes that began as low-profile ash-shields built from explosive eruptions resulting from magma rising through water-rich mega-regolith. As near-surface groundwater became less abundant due to depletion or freezing, explosivity diminished, and eruptions evolved into an effusive phase to form the lava flows inferred near the summits. Subsequently, the ash deposits were eroded to form the channels on the flanks of the paterae. Later image analyses, geologic mapping, and eruption modeling studies (Greeley and Crown, 1990; Crown et al., 1992; Crown and Greeley, 1993, 2007; Wilson and Head, 1994; Gregg et al., 1998; Gregg and Farley, 2006) further elucidated these processes.

The Hellas paterae were mapped as part of the post-Viking global geologic mapping program at a scale of 1:15 M, in which Greeley and Guest (1987) mapped Tyrrhena and Hadriaca Paterae and Tanaka and Scott (1987) mapped Amphitrites Patera and the now named Peneus Patera. Malea and Pityusa Paterae (named later) were mapped as volcanic materials (Pityusa Patera as a ‘volcanic patera’), and much of the entire area west–southwest of Hellas, now named Malea Planum, was mapped and interpreted to be composed of various volcanic units, including fluid lava flows and/or pyroclastic flows (Tanaka and Scott, 1987). Later, 1:5 M-scale geologic mapping was done by Tanaka and Leonard (1995; the published US G.S. map is by Leonard and Tanaka, 2001), in which they studied the general geology of the Hellas area and described both the basin-filling material and Malea Planum, including the paterae. Tanaka and Leonard (1995) suggested that the south side of the Hellas basin was filled with material most likely to be lava flows >1 km thick, erupted from Malea Planum (MOLA data do show a topography suggestive of flows from Malea Planum flowing into the basin), and later Tanaka et al. (2002) suggested catastrophic erosion of the southern Hellas basin rim occurred because of magmatic intrusion into volatile-rich rocks. Tanaka and Leonard (1995) mapped northern Malea Planum as containing upper-Hesperian to lower-Amazonian pyroclastic flow deposits, heavily dissected by the fluvial channels of Axius Valles, derived from Amphitrites and Peneus Paterae, and suggested that the distinctive caldera of Peneus indicated eruptions of massive volumes of magma, whereas the less pronounced morphology of Amphitrites was more indicative of a dissected shield that erupted lower volumes of magma. They noted a 20-km-diameter depression on the west flank of Amphitrites Patera that they thought might be a collapsed vent structure. Tanaka and Leonard (1995) analyzed the Hellas basin rim slopes dissected by Axius Valles,
and suggested that the presence of a hilly surface reflected degraded lava flows, lahars, or volcanlastic materials. In contrast, they mapped southern Malea Planum (i.e., south of Amphitrites and Peneus Paterae) as dominated by upper-Noachian to lower-Hesperian ridged plains, which they interpreted as low-viscosity lava flows from Amphitrites and Peneus.

Crumpler et al. (1996) analyzed calderas on Mars and described Amphitrites and Peneus Paterae based on Viking data. They described the radial and concentric pattern of mare-type ridges around Amphitrites and noted their resemblance to the so-called “arachnoids” on Venus, the category of low-profile volcano first seen in low-resolution Venera 15/16 images (Barsukov et al., 1986) and later in better detail in Magellan images (Head et al., 1992).

Some of the first Mars Global Surveyor (MGS) data analysis of this region was by Head and Pratt (2001a), who characterized the topography of the ‘Malea Planum volcanic province’ based on MOLA data. They found embayed craters, suggesting flooding by flows, and quantified the elevations of terrain, showing that Malea Planum stands some 1000–1500 km above Mars datum, and that Amphitrites is a distinctive shield 1.5 km high and contains a caldera 300–600 m deep, among other measurements.

With time, data from the current generation of Mars orbiters began to accumulate over the southern latitudes in the areas that still are difficult to observe because of atmospheric conditions, enabling testing of ideas that had been proposed previously. For example, Plescia (2003, 2004) used MOLA data and agreed that Amphitrites and Peneus are well-defined calderas based on their topography, but suggested that the features now called Malea and Pityusa Paterae are heavily eroded or buried craters and not necessarily volcanic vents. He also noted that the region is heavily mantled, with the terrain showing “scalloped” morphologies in MOC images, and that the paucity of small craters suggests extensive resurfacing.

Most recently, Kolb and Tanaka (in review) completed geological mapping of the south polar region and identified Malea and Pityusa Paterae as volcanoes, although heavily altered by other processes. Larson (2007), in an unpublished Master’s thesis,
conducted a thorough study of the paterae of Malea Planum using MOLA, MOC, and THEMIS data, and suggested that Malea and Pityusa Paterae might have been intrusive, and could not identify any lava flow features associated with them.

In summary, highland paterae appear to be the oldest recognized volcanoes on Mars that formed in association with edifice-building eruptions. Although earlier volcanism is inferred to have occurred on Mars (see e.g., Tanaka et al., 1992) there are no visible morphological indicators such as flows, and the interpretation is based on remote-sensing data that suggest iron and magnesium-rich compositions, such as basalt (McCord et al., 1982; Pinet and Chevrel, 1990; Bandfield et al., 2000). By analogy with lunar lava flows and flood basalts on Earth, the putative early Martian basalts are thought to have erupted from fissures, traces of which have been buried by their own products (i.e., ridged plains). Recent data have revealed evidence for extensive ridges interpreted to be exposed dikes related to flood basalt-like emplacement of the plains (e.g., Head et al., 2006). Thus, in this interpretation, highland paterae may represent a change in the style of volcanism on Mars from fissure eruptions (that typically involve rapid outpourings of large volumes of magma to produce vast sheets of flood lavas, e.g., Hesperia Planum) to local central vents that involved smaller “batches” of magma erupted at lower rates. We test these ideas in the work described below.

Fig. 2. THEMIS daytime-IR mosaics of the volcanoes of the CHVP, with spatial resolutions of 100 m/pixel. (a) Mosaics of Hadriaca Patera (left, caldera center coordinates 30° S, 93° E) and Tyrrhena Patera (right, caldera center coordinates 21° S, 106.5° E); (b) Mosaic of Amphitrites (caldera center coordinates 58.7° S, 60.7° E), Peneus (caldera center coordinates 57.7° S, 52.7° E), and Malea Paterae (caldera center coordinates 63.8° S, 52° E); (c) Mosaic of Pityusa Patera (caldera center coordinates 67° S, 38.5° E). For all mosaics, the black-lined regions delineate crater count areas for the “Edifice” as given in Table 1; the white-lined regions delineate crater count areas for the “Caldera” for all six volcanoes. The arrow in (b) points to a dome that could be a small volcanic construct. Mare-like ridges cut across the floors of Amphitrites, Peneus, and Malea Paterae, suggesting post-eruption deformation. Black zones are gaps in coverage. Image processing by Chris Edwards and Robin Ferguson, Arizona State University.
Fig. 3. Cumulative impact crater size–frequency distribution (SFD) plots for the six volcanoes of the CHVP: (a) Hadriaca Patera; (b) Tyrrhena Patera; (c) Amphitrites Patera; (d) Peneus Patera; (e) Malea Patera; (f) Pityusa Patera. Refer to Fig. 2 for count areas. For detailed crater statistics, see Table 1.
3. Data and methods

Image analyses constitute the primary data used in this study, coupled with crater counts, topographic measurements, and multispectral analyses, on which details are provided in appendix. The most complete areal coverage is from Mariner 9, Viking Orbiters 1-2, the Mars Express (MEX) High-Resolution Stereo Camera (HRSC: Neukum et al., 2004b), and the Mars Odyssey (MO) Thermal Emission Imaging System (THEMIS: Christensen et al., 2004). Very high-resolution images of limited coverage are available from the MGS Mars Orbiter Camera (MOC: Malin and Edgett, 2001) and the Mars Reconnaissance Orbiter (MRO) High-Resolution Imaging Science Experiment (HiRISE: McEwen et al., 2007) and Context Imager (CTX: Malin et al., 2007). In addition, visible and near-infrared multispectral data at high-spectral resolution are available for much of the area from the Mars Express Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité (OMEGA) spectrometer (Bibring et al., 2004). HRSC data are also used as 5-channel multispectral data. It should be noted, however, that images and multispectral data for geomorphic analyses are often compromised in the more southerly latitudes of Mars by clouds and dust in the atmosphere. Topographic data from the Mars Global Surveyor Mars Orbiter Laser Altimeter (MOLA: Zuber et al., 1992; Smith et al. 1999, 2001), MGS and MRO gravity data (Lemoine et al., 2001; G.A. Neumann, pers. comm., 2008), and subsurface imaging from the MEX Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS: Picardi et al., 2004) were also used in this study.

4. Results

In the following sections, we describe sets of paterae that constitute the CHVP, beginning with an overview of the well-known pair, Tyrrhena and Hadriaca Paterae northeast of the Hellas basin (Fig. 2a), discussion of the new data for Amphitrites and Peneus Paterae southwest of the Hellas basin (Fig. 2b), and consideration of the potential volcanic nature of Malea and Pityusa Paterae (Figs. 2b and c).

4.1. Tyrrhena and Hadriaca Paterae

Tyrrhena and Hadriaca Paterae are the northernmost volcanoes of the CHVP (Figs. 1 and 2a), and the least modified. Their geology has been relatively well described in Viking and post-Viking data analyses (e.g., Greeley and Spudis, 1981; Greeley and Crown, 1990; Crown et al., 1992; Crown and Greeley, 1993, 2007; Gregg et al., 1998; Gregg and Farley, 2006; Williams et al., 2007, 2008). The first volcanic stage to form the constructs of these paterae appears to have involved eruptions of ash, perhaps driven by water–magma interactions, to produce low-profile, shield-like edifices and large summit calderas. The volcanoes were then eroded, as evidenced by radial channels separated by mesas. This phase was followed by eruptions of fluid lavas that flooded the calderas and formed local flows on the flanks of the volcanoes (Greeley and Crown, 1990; Crown et al., 1992; Crown and Greeley, 1993). Since the cessation of volcanism and either concurrent or subsequent fluvial activity, the dominant process acting on Tyrrhena and Hadriaca Paterae has been differential aeolian erosion and deposition, as evidenced by bright mantling and dune deposits visible in MOC images (Williams et al., 2007).

Further studies based on HRSC, MOC, and THEMIS images include crater counts to assign cratering model ages (Williams et al., 2007, 2008) to units defined by the Viking image-based geological mapping (Gregg et al., 1998; Crown and Greeley, 2007). Both Hadriaca and Tyrrhena Paterae formed ~3.7–3.9 Ga, after the Hellas impact (~4 Ga: Werner and Neukum, 2003; Werner, 2005). Major volcanic event(s) occurred on their flanks and calderas.

Fig. 4. (Color online) HRSC false color mosaics of Hadriaca Patera (caldera center coordinates 30°S, 93°E) and Tyrrhena Patera (caldera center coordinates 21°S, 106.5°E). Note the blue patches in crater and channel floors and other topographic lows, and on some mesas. Previous HRSC color-spectral studies indicated such blue color units are consistent with mafic (typically basaltic) materials (McCord et al., 2007).
through ~3.3–3.7 Ga, and later resurfacing activity by fluvial, volcanic and/or aeolian processes occurred from ~3.3 to as recent as 1.1 Ga at Hadriaca Patera (Williams et al., 2007) and as recent as 0.8 Ga at Tyrrhena Patera (Williams et al., 2008).

For this project, we used THEMIS daytime-IR mosaics at 100 m/pixel spatial resolution as a consistent image base to perform crater counts to assess the ages of all six paterae in the CHVP (Figs. 2 and 3). The crater counting followed standard practices (Crater Statistics Analysis Group, 1979), and we determined $N(1)$ cratering model ages following the method of Hartmann and Neukum (2001); see also methods discussion in the appendix). Our results give a cratering model age of 3.7 Ga for Hadriaca Patera (whole volcano, excluding the caldera: Fig. 3a). This result is consistent with Williams et al. (2007), who counted smaller and different areas of the edifice on higher-resolution HRSC nadir images, and found $N(1)$ model ages ranging 3.7–3.9 Ga. For Tyrrhena Patera (whole volcano, excluding the caldera: Fig. 3b), our results give a cratering model age of 3.8 Ga. This result is in good agreement with Williams et al. (2008), who counted different areas of the edifice on HRSC nadir images and found $N(1)$ cratering model ages of formation ranging 3.7–4.0 Ga. Given the similarities in cratering model ages resulting from the Hartmann and Neukum (2001) method applied to both higher-resolution HRSC images and lower-resolution THEMIS day-IR mosaics, we have greater confidence in our crater counts using the THEMIS mosaics for the other four volcanoes in the CHVP that have not been studied previously with this technique.

We also used HRSC color images (Fig. 4) to assess variations in materials composing Hadriaca and Tyrrhena Paterae. The HRSC images show darker areas in topographic lows (crater and channel floors) or downslope from the summits, and in some cases on the tops of mesas, which we interpret as concentrations of basaltic material from the interiors of the volcanoes exposed by aeolian winnowing, or perhaps produced by glacial or fluvial erosion of underlying basalt and concentrated by local or regional winds (e.g., Baratoux et al., 2007b). This is consistent with previous interpretations of dark material observed in HRSC color data as being basaltic in composition (McCord et al., 2007). Alternatively, these darker areas could be basaltic sand or dust deposits transported from elsewhere on Mars and deposited by aeolian processes, although it is unclear where the long-distance source(s) are located. The relative brightness of these volcano flanks is indicative of considerable dust mantling, likely deposited...
by regional winds around the Hellas basin and attesting to the dominant role of current aeolian processes on Mars.

Finally, we compared MGS (Lemoine et al., 2001) and MRO gravity data (G.A. Neumann, pers. comm., 2008; gravity model MRO95a by Alexander Konopliv, JPL, available at: http://pds-geosciences.wustl.edu/missions/mro/gravity.htm) for the CHVP region (Fig. 1b). Results show strong positive gravity anomalies correlated with Tyrrhena, Hadriaca, and particularly Amphitrites Paterae (Lemoine et al., 2001), and much weaker anomalies for Peneus, Malea, and Pityusa Paterae. Although a comprehensive analysis of these martian gravity data has not been performed, we suggest that these data showing strong gravity anomalies could indicate the presence of relatively dense magma bodies underneath these edifices.

4.2. Amphitrites and Peneus Paterae

Most of this study focused on post-Viking images and other data to understand the four features in Malea Planum interpreted to be volcanoes: Amphitrites, Peneus, Malea, and Pityusa Paterae. In this section we describe Amphitrites and Peneus Paterae. MOC and HiRISE images and MOLA profiles (Fig. 5) provide tantalizing clues to the origin of these features. However, MOC high-resolution frames (~4 m/pixel) are isolated and cover too small an area to enable an integrated analysis of the features. HRSC nadir (~12 m/pixel) and THEMIS visible (18 or 36 m/pixel) images, along with HRSC color (Fig. 6) and THEMIS (Fig. 2b) daytime-IR images, both at 100 m/pixel, provide coverage over both features under relatively clear atmospheric conditions.

MOLA profiles (Fig. 5) show that Amphitrites Patera is about 280 km across and stands 1000–1300 m above the surrounding plains, forming a broad shield-shaped edifice superposed on older ridged plains of Malea Planum to the south. The summit of Amphitrites Patera contains a caldera 112 km in diameter within a floor 300–600 m below the rim. Much of the surface of Amphitrites is modified by Barnard crater, a 130 km diameter central-ring impact structure superposed on the southern flank of the volcano. Although ejecta flow lobes from the impact mantle the patera floor, some process(es) (e.g., periglacial modification, aeolian mantling, or post-impact eruptions) have erased smaller features, including secondary impact craters.

Where not obviously covered by ejecta from large impacts, the flanks of Amphitrites consist of ridges as large as 8 km wide by 100 km long that are approximately radial to the caldera (Fig. 2b). Segments of channel-like depressions 5 km wide and 35 km long occur between some of the ridges. Lobate flows are seen in some of these depressions and in many parts of the flank, especially in the western zone (Fig. 7). Cross-sections of flank materials exposed in the channel walls do not appear to be layered, at least at the limit of MOC resolution (~4 m/pixel). Smaller channel segments about 300 m wide and chains of small (200 m), elongate craters suggest the presence of lava flow channels and partly collapsed lava tubes (Fig. 8). Although the crater chains are approximately radial to Barnard crater and could be secondary craters, they appear to follow local topography, which would not be expected for ballistically emplaced impacts. A small (~18 km in diameter) dome on the southwest flank of Amphitrites Patera could be a volcanic construct (Fig. 2b).

Fig. 7. (a) MOLA context for Amphitrites Patera (16 pixel/deg). (b and c) THEMIS VIS images of the patera’s floor, showing lobate-like patterns marking the scarps of scalloped and pitted terrain. The subdued and “softened” appearance suggests geomorphic degradation. (b) THEMIS VIS V06577004 (17 m/pixel). (c) THEMIS VIS V14889005 (34 m/pixel).
Leonard and Tanaka (2001) suggested that late-Hesperian to early-Amazonian pyroclastic deposits from both Amphitrites and Peneus Paterae flowed north over the rim of the Hellas basin. These relative ages correspond to cratering model ages \( \approx 3.5 \) Ga to as young as 2.1 Ga (the Hesperian–Amazonian boundary occurs at 3.3 Ga (Neukum system) to 2.9 Ga (Hartmann system) as given in Hartmann and Neukum, 2001; Hartmann, 2005 lists the boundary as 3.3–2.0 Ga). We tested this hypothesis by selecting a section of dissected terrain north of Peneus and Amphitrites Paterae on the THEMIS 100 m/pixel mosaic for crater counting (Fig. 2b). We found a cratering model age of \( \approx 3.8 \) Ga for this dissected unit (Fig. 9), indicating that its formation occurred much earlier in martian history. Leonard and Tanaka (2001) also suggested that late-Noachian to early-Hesperian lava flows make up the ridged plains south of Amphitrites and Peneus Paterae (\( \approx 3.8–3.5 \) Ga: Hartmann and Neukum, 2001). We used the terrain surrounding the Pityusa Patera caldera (the Pityusa “edifice”): Table 1 as an example of ridged plains, and we found a cratering model age of \( \approx 3.8 \) Ga for this unit. This result is consistent with the mapping of Leonard and Tanaka (2001), indicating the ridged plains of Malea Planum are late-Noachian in age. For Amphitrites Patera as a whole (whole volcano, excluding the caldera: Figs. 2b and 3c), we determined a cratering model age of \( \approx 3.6 \) Ga. This is slightly younger within uncertainties with earlier results for the formation of Hadriaca and Tyrrhena Paterae (Williams et al., 2007, 2008), and younger than the ridged plains of Malea Planum. Amphitrites’ caldera also has a cratering model age of \( \approx 3.6 \) Ga.

The Amphitrites Patera caldera (Figs. 2b, 6, and 7) is ringed with discontinuous, shallow graben, and subtle ridges. Much of the caldera floor is smooth in comparison to the flanks of the volcano. Ejecta flow lobes from Barnard crater cover parts of the southern floor, and secondary craters and ejecta from smaller, relatively fresh impact craters are traced over parts of the northern and eastern floor. However, the central and western parts of the caldera floor are smooth and lack obvious chains of secondary craters from Barnard crater and are interpreted to post-date the impact. The caldera floor is disrupted by mare-like ridges, some of which extend over the caldera rim onto the northern flank, suggesting post-eruption deformation of the summit area. Because of atmospheric effects in the HRSC color data, the extent of dark material in the SW floor of the caldera and southeastern flank of the volcano is unclear (Fig. 6).

Peneus Patera (Figs. 2b, 6, and 10) is about 290 km across and, unlike Amphitrites Patera, shows little topographic relief from its outer flanks to the central caldera (Fig. 5). Radial ridges and channel segments are present, but are less prominent than on Amphitrites and are seen mostly on the northern and eastern flanks of the volcano. Similar features might also be on the other flanks, but ejecta from impact craters are superposed on the surface, masking the underlying features. The craters include the 100 km diameter impact crater Henry Moore, the crater Chaman on the southern flank and the crater Elia on the northwestern flank (Fig. 2b). Small sinuous channels \( \approx 200 \) m wide and local flows are also seen in the topographically lower parts of the flanks of Peneus Patera. Our crater counts on the THEMIS mosaic indicate a cratering model age of \( \approx 3.8 \) Ga (total shield, excluding the caldera: Fig. 3d). This age is equivalent to that of the dissected and ridged plains in Malea Planum, and suggests that volcanic activity at Peneus began before that at Amphitrites. The caldera of Peneus
chronology model of Neukum (1983), Hartmann and Neukum (2001), and Ivanov (2001):

...data (Fig. 6) show a low albedo zone in the northern half of irregular depressions that might be collapse features. HRSC color flat and smooth except for two wrinkle ridges and a zone of Amphitrites and the outer margins of the Peneus caldera. This covers about 2% of the area and is found primarily on the flanks of...using THEMIS data shows that this scalloped and pitted terrain at this latitude, this scalloped and pitted terrain is thought to involve surface degradation resulting from sublimation of near-water ice (Lefort et al., 2005; Russell et al., 2005; Morgenstern et al., 2007). Our preliminary mapping of the region using THEMIS data shows that this scalloped and pitted terrain covers about 2% of the area and is found primarily on the flanks of Amphitrites and the outer margins of the Peneus caldera. This occurrence could reflect the presence of ash or other fine-grained material capable of containing water or ice at the time of formation of the terrain. Most of the caldera floor is generally flat and smooth except for two wrinkle ridges and a zone of irregular depressions that might be collapse features. HRSC color data (Fig. 6) show a low albedo zone in the northern half of the caldera floor. We interpret this zone to be residual concentrations of underlying basaltic material exposed by aeolian winnowing (perhaps buried lava flows or pyroclastic material) covered by dust. (This region is also noted for many dust devil tracks, and multiple active dust devils observed in HRSC and SRC images, see Oberst et al., 2008). Alternatively, aeolian processes could cause basaltic sand to accumulate in topographic lows. However, the HRSC preliminary DTM for orbit 2133 (spatial resolution 200 m/pixel) shows that the west-central interior floor has a similar elevation as the dark zone: yet there are no dark deposits there, possibly supporting the volcanic interpretation for the dark zone.

The surfaces of both paterae have a “softened” appearance, typical of terrains in the higher latitudes of Mars and suggestive of modification by periglacial processes such as downslope movement of fragmental material aided by incorporated water and ice (Squyres and Carr, 1986). The presence of volatiles in surface materials at the time of modification is also suggested by abundant “ejecta flow” or pedestal craters (Fig. 11), considered to represent impacts into volatile-rich targets (Carr et al., 1977b; Barlow et al., 2000). The occurrence of mass-wasting flow lobes on the inner walls of Barnard and the other large impact craters is consistent with the presence of fragmental material lubricated by water or ice (e.g., Marchant and Head, 2007). HiRISE and CTX images of this region show polygonal fractures and mounds in and around the scalloped and pitted terrain (Figs. 12 and 13), thought...
to be indicative periglacial processes involving water ice sublimation (Lefort et al., 2005; Levy and Head, 2005; Morgenstern et al., 2007; Zanetti et al., 2008). Furthermore, the widespread presence of pedestal craters (also called “perched” craters: McCauley, 1973; Kadish et al., 2008a, b) suggest that differences exist in the blockiness of the ejecta compared to the surrounding terrain, leading to differences in the thermal regime and differential devolatilization of the materials, in which the ejecta is more resistant to erosion (Meresse et al., 2006). MOC images show that the ejecta for these craters is surfaced with boulders, supporting the ideas regarding differential erosion.

In summary, the evidence supporting the volcanic hypothesis for Amphitrites Patera include: (a) the shield-like topography and dissected flanks, similar to Tyrrhena and Hadriaca; (b) the cratering model age similarity (~3.6 Ga) to a time of inferred volcanic activity at Tyrrhena and Hadriaca; (c) a strong positive gravity anomaly, perhaps indicative of a dense subsurface magma body, similar to that observed at Tyrrhena and Hadriaca; (d) dark material in color data, perhaps evidence of residual concentrations of mafic volcanics (alternatively, aeolian-transported basaltic sand and dust), similar to that observed at Tyrrhena and Hadriaca; and (e) rare evidence of radial channel segments (perhaps collapsed lava tubes?).

The evidence supporting a volcanic hypothesis for Peneus Patera is somewhat more ambiguous: (a) a caldera-like central depression, but no positive-relief edifice; (b) a cratering model age (~3.8 Ga) correlative with the formation ages of Tyrrhena, Hadriaca and the plains of Malea Planum; (c) a positive (although weak) gravity anomaly; and (d) dark material in color data in the north-central Peneus floor, perhaps evidence of residual concentrations of mafic volcanics (alternatively, aeolian-transported basaltic sand and dust), similar to that observed at Tyrrhena and Hadriaca. No clear evidence of lava flows, flow fronts, small shields or cones, or fine-scale layering has thus far been found in high-resolution SRC, MOC, CTX, or HiRISE images, even though coverage is scarce; rather, these images show pervasive scalloped and pitted terrain (i.e., large-scale layering) and buried and exhumed impact craters, which may indicate emplacement of pyroclastic, aeolian or circum-polar mantles (e.g., Head and Pratt, 2001b). These results suggest to us that Peneus Patera may be best interpreted as an “embedded caldera”, in which multiple episodes of explosion and collapse produced the multiple grabin in its interior. Nevertheless, it is clear that, at the latitude of Amphitrites and Peneus (~58°S), repeated surface modification by aeolian and periglacial processes and/or emplacement of circum-polar mantles may have destroyed or hidden much of the evidence of their ancient volcanism.

4.3. Malea and Pityusa Paterae

MOLA data (Figs. 1 and 5) show that Malea and Pityusa Paterae consist of two irregular depressions in the surface of the ridged plains of Malea Planum. Relatively weak gravity anomalies (Fig. 1b) occur in association with these features (Lemoine et al., 2001; G.A. Neumann, pers. comm., 2008). The floor of Malea
Patera lies at an average of ~10 m in elevation, below a south and southwest topographic high with a maximum elevation ~1600–1800 m. The north end of the Malea Patera floor is bordered by a ~1000 m topographic high, sloping up ~0.3° before descending into Peneus Patera. The “rim” of Malea Patera is ill-defined in MOLA and THEMIS data; wrinkle ridges in part define a possible caldera (Fig. 2b). Similar to Peneus and Amphitrites, the floor of Malea Patera contains wrinkle ridges, unusual heart-shaped layered mesa 35 km wide (W–E) by 37 km long (N–S). MOC and THEMIS images (Fig. 14) show that this mesa is layered on its margin, and has an upper surface that contains dust devil tracks and many fine pits at the tens to hundreds of meters scale, which is expected at higher southern latitudes (Head et al., 2003). However, Malea lacks the scalloped and pitted terrain found on Peneus and Amphitrites, suggesting that Malea’s floor materials are in some way different from those in Peneus and Amphitrites. Subsurface data from several MARSIS tracks show an apparent layer under the center of Malea Patera (Fig. 15) at least 100 km long and at a depth of about 300–500 m; however, it is currently unclear what this layer is, as its location is not the same as the heart-shaped layered mesa. Possibilities include lava flow, pyroclastic deposits, or ice, each of which has implications for the types of geologic activity that occurred within Malea Patera. Because this is a relatively shallow feature and MARSIS is better at imaging deeper subsurface features (> 1 km: Picardi et al., 2004, 2005; Plaut et al., 2007), it may require higher spatial resolution SHARAD data to better understand this interface. Crater counts on the THEMIS 100 m daytime-IR mosaic found a cratering model age of ~3.8 Ga for Malea Patera, suggesting a very old structure.

Comparison of the HRSC nadir and color images yielded identification of several dark features within the inner rim of Malea Patera (Fig. 16). These appear to be point sources of dark material that, although being modified by local winds, are not accumulations in topographic lows, like many of the other dark deposits in the CHVP. We suggest these may be point sources of volcanic materials, perhaps vents being exhumed. We compared the HRSC color data to the OMEGA data for this orbit using several different techniques (principal component analysis: Pinet et al., 2007; nonlinear spectral unmixing: Poulet et al., 2007; linear spectral unmixing: Combe et al., 2008a, b) (Fig. 17a); OMEGA data unambiguously indicate the composition of this dark material is consistent with mafic volcanics, rich in clinopyroxene, orthopyroxene, and localized deposits of olivine. Additionally, the spectroscopic information inferred from OMEGA data supports the idea of a basaltic material with close characteristics to those observed on the Syrtis Major shield (Baratoux et al., 2007a, b; Pinet et al., 2007; Poulet et al., 2007), that can be exposed or seen intermittently through the dust

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Fig. 11. Portion of THEMIS mosaic of a relatively fresh “ejecta-flow” crater, 5 km in diameter southwest of the Peneus Patera caldera rim. Such crater ejecta patterns represent impacts into volatile-rich target materials (Cars et al., 1977b; Barlow et al., 2000).

Fig. 12. (a) Part of HRSC nadir image showing a relatively young, buried and exhumed impact crater on the northern part of Amphitrites caldera floor, and the unusual irregular pits a few hundred meters across within the ejecta zone of the crater (HRSC image H2525_0000.nd4; 12.5 m/pixel). Inset is part of HiRISE image PSP_004867_1220_RED, showing greater detail on the scalloped and pitted terrain. (b) Portion of THEMIS mosaic showing the low-temperature signature correlated with the ejecta zone of the crater.
coverage exhibiting clear ferric oxide phase characteristics typical of bright terrains across Mars.

HRSC images are also used as 5-band multispectral data (440 nm—blue, 530 nm—green, 650 nm—nadir, 750 nm—red, 970 nm—infrared), after calibration into radiance factor $I/F$ ($I$: observed surface radiance, $F$: observed solar flux or irradiance) and corrected for incidence angle variations (division by the cosine of the incidence angle). Those spectra are mostly sensitive to two surface materials (dark mafics and bright red iron oxides) represented by two image spectral endmembers, and shade. We have found that we can use the spectral unmixing method of Combe et al. (2008b) on multispectral HRSC data to map the proportions of dark material (Combe and McCord, 2008) in the CHVP (Fig. 17b), to better identify the extents and locations of residual concentrations of possible volcanic materials (e.g., SW Malea Patera floor). In future studies we will be able to target these locations with OMEGA data to assess if any compositional variations are present in these dark materials (e.g., Tirsch et al., 2008).

In MOLA data, Pityusa Patera occurs as an irregular central depression surrounded by a pronounced rim on the south, west, and north sides (Fig. 2c), in which the central depression contains: (a) a southeastern rugged zone of layered hills, (b) a northern dark sand dune field, and (c) a west-central, bright, smooth, irregular, cratered plateau. The lowest levels of the Pityusa central depression are around 0 m elevation, and the bright plateau rises to $\sim$300 m. The central depression is $\sim$170 km wide (W–E) by $\sim$200 km long (N–S), and the rim is crosscut by radial to sub-
parallel wrinkle ridges. The surrounding plains contain many large craters and near-concentric wrinkle ridges. Crater counts on the THEMIS 100 m day-IR mosaic (Fig. 2c) give a cratering model age of ~3.8 Ga for the feature, and ~3.6 for the central depression (dominated by the bright irregular plateau). Similar to Malea Patera, Pityusa lacks the scalloped and pitted terrain found on Peneus and Amphitrites, but does contain many pedestal craters. MOC and THEMIS data reveal details about the materials in the Pityusa central depression (Figs. 18 and 19). The ~100 km wide by ~120 km long bright, irregular plateau is quite diverse, with a striated and heavily cratered surface on its north side, and a heavily cratered surface that lacks striations on the south side. The plateau has pits both lacking and containing dark sand, in which wind streaks from the filled pits point to and feed the dark dune field to the north. The hills in the southeastern part of the depression are layered on the scale of hundreds of meters, and heavily eroded. Between the hills the surface is cut by sub-parallel sets of ridges and grooves, indicative of extensive degradation of these layered materials.

We used OMEGA data (Fig. 20) to assess the composition of the dark sand dune field in Pityusa Patera, in the form of modal mineralogy derived using the nonlinear unmixing model of Shkuratov et al. (1999), Poulet et al. (2002), and Poulet and Erard (2004). The dark sands are composed mostly of plagioclase and high-Ca pyroxene, with smaller amounts of low-Ca pyroxene, olivine, and dust (Table 2). We interpret this composition as basaltic sand, derived from mafic volcanics.

The nature of the bright, irregular plateau is particularly puzzling (Figs. 18 and 19). Based on MOLA data it is several hundred meters thick. It has a well-defined boundary around its perimeter, and appears well-consolidated. It is unclear whether the layered hills to the southeast are remnants of part of the plateau that has been eroded. It is also unclear whether the dark sands are being exposed from underneath the plateau, or whether they have simply been deposited north of the plateau by winds and the dark sand originates elsewhere on Mars. Although a definitive explanation for the bright plateau cannot be made with available data, we suggest that it, and perhaps the heart-shaped mesa in Malea Patera consists of ignimbrite deposits. Ignimbrites (Marshall, 1935; Gilbert, 1938) are pyroclastic flow deposits (also called ash-flow tuffs), and may be welded or unwelded and composed of mostly pumice and ash (Schminke, 2004). Welded ignimbrites can be somewhat more resistant to erosion,
resulting from the welding of the pyroclastic particles that occurs by the heat retained in the flow after motion ceases. A recent review of studies of the Medusae Fossae Formation suggests that it most likely contains the remnants of martian ignimbrite deposits (Scott and Tanaka, 1982; Zimbelman et al., 1998; see discussion in Mandt et al., 2007, 2008), and we note that there are some morphological similarities between the Pityusa irregular plateau and at least one terrestrial ignimbrite deposit (cf., Mandt et al., 2008, Fig. 10).

In summary, our overview of the available data for Malea and Pityusa Paterae strengthens the case for the role of volcanism in the formation of these features, but does not categorically demonstrate that these are volcanoes. In fact, their morphologies are quite different from Tyrrhena, Hadriaca, and Amphitrites.
Paterae. Both Malea and Pityusa formed ~3.8 Ga, at the same time as Tyrrhena, Hadriaca, and Peneus Paterae, but before Amphitrites Patera. Like Peneus, but unlike Tyrrhena, Hadriaca, or Amphitrites, these features have no well-defined volcanic edifice; rather they have central depressions formed in the ridged plains of Malea Planum. Like Peneus, but unlike Tyrrhena, Hadriaca, or Amphitrites, these features have no strong positive gravity anomalies, perhaps indicative of a different style of volcanism (more explosive), or simply of collapse after early eruption(s) emptied the magma chambers, forming the central depressions. Dark materials detected in HRSC color data are identified in OMEGA data unambiguously as basaltic in composition; however, their provenance as localized mafic volcanics, particularly at Pityusa, cannot be definitively determined. No lava flows, flow fronts, or unequivocal vents have been identified at Malea and Pityusa; however, we propose that the heart-shaped mesa at Malea and the bright, irregular plateau at Pityusa could be ignimbrite deposits. If so, these would indicate a different style of volcanism at Malea and Pityusa compared to the other volcanoes in the Province.

5. Discussion

5.1. Ages

Crater size–frequency distribution (CFD) results (Table 1, Fig. 21) show that the six highland paterae are in the same age-range, but that Tyrrhena, Peneus, Malea, and Pityusa are slightly older at 3.8 Ga, while Hadriaca and Amphitrites are younger at 3.7 and 3.6 Ga, respectively. These differences may not be that significant, considering the 100 Ma error bar on the Hartmann and Neukum technique. However, the caldera ages all range from 3.8 to 3.2 Ga, and are substantially older than those observed on the floors of the Tharsis volcanoes, most of which are younger than 0.5 Ga (Neukum et al., 2004b). Based on the observations from the new data presented here and from previous studies, we suggest that the main constructs of the highland patera around the Hellas basin formed over the period of 4–3.6 Ga, making them the oldest preserved volcanoes on Mars and (in agreement with previous studies) reflecting a change in eruptive style from the putative earlier fissure-fed flood eruptions to local edifice-building eruptions. The ages of Peneus, Malea, and Pityusa Paterae are also consistent with the ages of valley networks (~3.7–3.5 Ga: Fassett and Head, 2008) and the time when extensive amounts of water existed (at least temporarily) on the surface (e.g., Carr, 1996). If Malea and Pityusa Paterae are the Martian equivalent of ancient giant calderas or “supervolcanoes” (e.g., Self, 2006) that produced ignimbrite deposits, then these eruptions likely involved substantial amounts of volatiles (such as water) in the magma. If early Mars was characterized by generally wetter conditions (i.e., abundant groundwater in the shallow crust), then these conditions might have enabled these types of large explosive eruptions.

5.2. Structure and topography

MOLA profiles and the MGS (Lemoine et al., 2001) and MRO gravity data show dissimilarities among the six volcanoes of the CHVP. The three volcanoes with positive-relief edifices in MOLA data (Tyrrhena, Hadriaca, and Amphitrites) also have strong positive gravity anomalies, perhaps indicative of dense magma bodies below the surface. The other three volcanoes (Peneus, Malea, and Pityusa) have central depressions within the surrounding plains, and lack both the shield-like edifices and the strong positive gravity anomalies observed at the other three volcanoes. If these paterae are the remnants of giant Martian calderas that produced explosive eruptions and that, in the case of Malea and Pityusa Paterae, produced ignimbrite deposits, then there was a larger diversity of volcanic eruption styles in the CHVP than has previously been considered.

5.3. Morphology and surface degradation

If this is a volcanic province, then where are all the volcanic vents and lava flow boundaries? The detailed MOC, THEMIS, and
HRSC images show that the original volcanic surface of the CHVP is covered by a surface mantle material with a thickness of tens to several hundreds of meters. The low-density distribution of fresh, small (<500 m diameter) impact craters on much of the surface of the CHVP, and the generally smoothed appearance of the surface at the scale of hundreds of meters, are indicative of relatively recent formation of much of the surface material composing the mantle cover (likely of Amazonian age). We suggest that the nature of the material is closely related to deposition of aeolian dust and sand in combination with enrichment by water ice from condensation of atmospheric water vapor, and from areal variations in seasonal polar cap deposits due to periodic variations of Mars’ orbital parameters. For example, throughout the Hesperian, extensive south circum-polar deposits (the Dorsa Argentea Formation, DAF) were emplaced. One interpretation is that these represent south polar and related ice-rich deposits (Head and Pratt, 2001b) that could have been characterized by mantling deposits that extended well beyond the border of the DAF to lower latitudes.

As we have shown, the volcanic morphology of the paterae south of Hellas at regional scales (tens to hundreds of kilometers) has some similarities and some differences to Tyrrhena and Hadriaca Paterae. However, based on MOC, CTX, and HiRISE images, the surface morphology of the southern part of the CHVP at the scale of tens to one hundred meters looks mostly identical, due to widespread manifestations of the periglacial features (e.g., mounds, polygonal fractures, scalloped and pitted terrain). These features formed because of freezing and ice enrichment of...
the surface mantle and former volcanic deposits. The dominant type of the permafrost features in the Province, as observed in HiRISE images, is a polygonal relief formed by frost cracking. The features form a polygonal system of the shallow troughs, which surround central mounds a few meters in size (see also Marchant and Head, 2007). These permafrost features are mostly found in the area of Amphitrities and Peneus Paterae (Fig. 13) and occur in and around scalloped depressions (Plescia, 2003; Lefort et al., 2005). A combination of processes such as sublimation of interstitial ice and wind deflation is the main mechanism for the formation of the depressions (Costard et al., 2008; Zanetti et al., 2008). These processes are widespread within the area of the Amphitrities and Peneus Paterae. In contrast, the ice-rich deposits to the south are less disturbed by these processes. Nevertheless, it is now clear that the presence of the ice in the surface materials within the CHVP enabled the smoothing of the surface relief, because of sublimation, cryogenic weathering, and ground ice creep processes, all of which masks most of the evidence of the ancient volcanism.

Table 2

<table>
<thead>
<tr>
<th>Location of unit</th>
<th>Mineral component</th>
<th>Abundance (vol%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pityusa Patera dark dune field</td>
<td>Plagioclase</td>
<td>48 ± 6</td>
</tr>
<tr>
<td></td>
<td>High-Ca pyroxene</td>
<td>26 ± 3</td>
</tr>
<tr>
<td></td>
<td>Low-Ca pyroxene</td>
<td>8 ± 2</td>
</tr>
<tr>
<td></td>
<td>Olivine (100 μm)</td>
<td>5 ± 4</td>
</tr>
<tr>
<td></td>
<td>Dust</td>
<td>13 ± 7</td>
</tr>
</tbody>
</table>

5.4. Compositional information

Previous studies of the Martian surface based on thermal-infrared and visible/near-infrared spectroscopy (e.g., Bandfield et al., 2000; Bibring et al., 2005; McCord et al., 2007) indicated that materials that appear dark blue to black in "true color" images have compositions consistent with basaltic volcanic deposits. HRSC color data at 50–100 m/pixel cover wide areas of the surface, such that through the application of spectral deconvolution method (Combe et al., 2008) we can map these images for percentage of dark material in a given region (Fig. 17). Clearly, there are many areas in the CHVP that contain this dark material; the key question then becomes whether this dark material is concentrated from underlying basaltic volcanics and exposed by aeolian winnowing or produced by glacial or fluvial erosion and concentrated by local winds (e.g., Baratoux et al., 2007a,b), or is it basaltic sand and dust transported from elsewhere on Mars by regional winds? As there is no direct indication of source regions outside the CHVP, and there are some rare outcrops clearly exposed on steep slopes such as crater or caldera rims (Fig. 16), we favor the interpretation that the dark material is concentrated from underlying basaltic volcanics. However, additional high-resolution imaging (HIRISE) and spectral analysis (CRISM) is required to better address this question.

6. Future work

Now that we have completed our initial reconnaissance of the CHVP, the next step is to focus future studies on specific aspects of the CHVP, to better assess the volcanic nature of the exposed surface. The following types of analyses are needed:

1. Use available MOC, SRC, HRSC, and THEMIS images to study in detail all locations of dark material exposed in the CHVP, and, if possible, acquire new HIRISE and CTX images of these features to assess their geologic nature.

2. Conduct a complete spectral deconvolution study of all good quality HRSC color data covering the CHVP, to assess the proportions of partially buried dark material in the surface and their relationship to exposed dark material.

3. Analyze OMEGA and CRISM data (as it become available) of exposed dark material to assess compositional variability.

4. Expand the study of MARSIS data and include SHARAD data to investigate the nature of layering at key locations throughout the CHVP.

Additionally, there is a region of western Promethei Terra on the east side of the Hellas basin (36°–50° S, 90°–106° E) that contains smooth plains interpreted to be volcanic materials (Raitala et al., 2007) that needs to be more thoroughly studied. As we have demonstrated in this paper, only with integrated data analyses of all available spacecraft data for this region will it be possible to unravel the nature of the ancient volcanism and the complex geologic history of the Circum–Hellas Volcanic Province.

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Appendix A

A.1. Crater count methods

Crater size–frequency distributions (CFDs) for the six volcanoes of the CHVP were obtained to derive a general sequence of events and their relation to general Martian history. We produced mosaics covering Tyrrhena, Hadrira, Amphitrites, Peneus, Malea, and Pityusa Paterae using the THEMIS daytime-IR data at 100 m/pixel as a standardized base. Because there is controversy regarding CFDs for dating surfaces on Mars especially with regard to estimating "absolute" dates and the use of statistics based on small craters (McEwen et al., 2005), our approach in this study was to: (1) use craters > 800 m diameter to avoid the addition of secondary craters which would yield erroneously old ages, and (2) use the results primarily for age comparisons within individual volcanoes, and for comparisons among the patera and other volcanoes on Mars (i.e., even though the "absolute" dates might...
corresponding statistical errors (see e.g., Hartmann, 1966; Neukum and Wise, 1976; Crater Analysis Techniques Working Group, 1979; Neukum and Hiller, 1981; Neukum, 1983) using the CRATERSTATS package developed by the Free University, Berlin (Michael and Neukum, 2008: http://hrscview.fu-berlin.de/crater-stats.html). In this technique, the cumulative CFDs were analyzed to determine crater densities at specific reference diameters, and cratering model ages following Hartmann and Neukum (2001). Cumulative crater densities for 1-, 2-, 5-, 10- and 16-km diameter craters were used by Hartmann and Neukum (2001) to assess relative ages for martian geologic units and to place units into the martian chronologic system using key units as referents (e.g., Tanaka et al., 1992). In general, the lower the crater density (the fewer the craters that formed or have been retained (preserved) on the surface), the younger the age. A cratering model age (in Ga) is calculated from the cumulative crater density at a reference crater diameter of 1 km using an established cratering chronology model for Mars (Neukum, 1983; Hartmann and Neukum, 2001; Ivanov, 2001), which is typically extrapolated from the lunar model (in which crater frequencies are correlated with radiometric ages from Apollo samples) that has been adjusted for the different orbital mechanics, crater scaling, and impact flux for Mars relative to the Moon. The transfer of the lunar cratering chronology model to Mars may introduce a systematic error of up to a factor of 2. This means that the typical uncertainty in cratering model ages could vary by a factor of 2 for ages < 3.5 Ga (in the constant flux range), whereas the uncertainty is about ± 100 Ma for ages > 3.5 Ga (Hartmann and Neukum, 2001).

Extensive testing and application of these techniques, however, have shown that the applied martian cratering chronology model results in ages for basin formation and volcanic surfaces that are in good agreement with Martian meteorite crystallization ages with respect to “peak” activity periods (Neukum et al., 2007), which suggests that the chronology model is correct within an uncertainty of less than 20% (Werner, 2005). Specific error bars for each cratering model age are included in Table 1. The results obtained for Hadriaca Patera and Tyrrhena Patera were compared with previous CFDs made from counts on higher-resolution HRSC images (Williams et al. 2007, 2008). Ages for the “Edifice” were obtained from homogeneous surfaces that are considered to represent the main structure of the volcano. “Caldera” ages were obtained for the smoothest surfaces that are considered to represent eruptions of flood lavas or ash, or deposits of non-volcanic origin. All of these surfaces have been highly modified by degradational processes. In most cases, CFDs show “kinks” in the cumulative distributions that are considered to represent resurfacing events, in which the smaller craters are obliterated, while the larger craters are still visible and can be counted. Resurfacing events can include mantling by windblown, volcanic, or other deposits, or surface degradation processes, such as mass wasting or periglacial activity, that might differentially remove smaller craters. Because of the uncertainty in the process(es) leading to these “kinks,” and the focus of this study on the major volcanic events, this aspect of the CFDs is not considered.

A.2. Spectroscopy methods: Fig. 17

OMEGA spectra are calibrated into radiance factor (LIF) and corrected for atmospheric absorptions using an empirical method, which consists of using a synthetic atmospheric transmittance corresponding to the ratio of two spectra acquired at the top and bottom of Olympus Mons and scaling it to the depth of the 2 μm CO₂ band. We restricted the analysis to the OMEGA Short Wavelength Infrared (SWIR) detector (0.96–2.57 μm) to eliminate inter-detector calibration and registration discrepancies. Furthermore, the SWIR detector covers a wavelength range that contains the most diagnostic bands.

The method of spectral unmixing applied here (Combe et al., 2008) is a pixel-by-pixel spectral linear deconvolution that relies on a reference spectral library of 20 pure minerals. Minerals represented include mafics, iron oxides, sulfates, clays, carbonates, and water ice. Two modeled spectra account for atmosphere and surface photometric effects. Each OMEGA spectrum is modeled by a maximum of four mineral components. This limitation prevents insignificant endmembers from being included in the model. The maps of the minerals vary with abundances, but they are not proportions, since mixing coefficients are also sensitive to grain size variations.

A.3. Spectroscopy methods: Fig. 18 and Table 2

Modal mineralogy is derived using the nonlinear unmixing modeling based on the Shkuratov radiative transfer model (Shkuratov et al., 1999; Poulet et al., 2002; Poulet and Erard, 2004). Poulet et al. (2002) showed the degree of realism and efficiency of this model relative to other scattering models, and in particular to the Hapke model and its derivatives. This model has also been tested to determine the type of mixture (sand, areal, or bedrock), the relative proportions, and the grain sizes of components of laboratory mineral samples (Poulet and Erard, 2004), as well as applied to spectra of several planetary surfaces. For each spectrum the model had to satisfy two major constraints: the depth and the shape of the absorption(s) band(s) and the average value of the reflectance. One additional free parameter was used to modestly adjust the continuum spectral slope resulting from aerosols and/or photometric effects. The data were fit using a simplex minimization algorithm.

Although nonlinear mixing of reflectance spectra is a powerful way to explore data sets, the method has limitations. First, the set of optical constants used as endmembers must be representative of materials that are under study. Because we apply the nonlinear unmixing method to low albedo regions that are dominated by basaltic minerals, the minerals used in this paper are pyroxene (both low- and high-calcium), olivine (both Fe- and Mg-rich), feldspar (labradorite) and a dark oxide (magnetite). The optical constants were derived using the scheme described in Poulet and Erard (2004) from reflectance spectra.

References


