Icarus 205 (2010) 259–268

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Scalloped terrains in the Peneus and Amphitrites Paterae region of Mars as observed by HiRISE

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ARTICLE INFO

Article history:
Received 10 October 2008
Revised 15 May 2009
Accepted 3 June 2009
Available online 14 June 2009

Keywords:
Mars, Surface
Geological processes
Ices

ABSTRACT

The Peneus and Amphitrites Paterae region of Mars displays large areas of smooth, geologically young terrains overlying a rougher and older topography. These terrains may be remnants of the mid-latitude mantle deposit, which is thought to be composed of ice-rich material originating from airfall deposition during a high-obliquity period less than 5 Ma ago. Within these terrains, there are several types of potentially periglacial features. In particular, there are networks of polygonal cracks and scalloped-shaped depressions, which are similar to features found in Utopia Planitia in the northern hemisphere. This area also displays knobby terrain similar to the so-called "basketball terrains" of the mid and high martian latitudes. We use recent high resolution images from the High Resolution Imaging Science Experiment (HiRISE) along with data from previous Mars missions to study the small-scale morphology of the scalloped terrains, and associated polygon network and knobby terrains. We compare these with the features observed in Utopia Planitia and attempt to determine their formation process. While the two sites share many general features, scallops in Peneus/Amphitrites Paterae lack the diverse polygon network (i.e. there is little variation in the polygon sizes and shapes) and large curvilinear ridges observed in Utopia Planitia. This points to a more homogeneous ice content within the substrate in the Peneus/Amphitrites Paterae region and implies that scallop formation is independent of polygon formation. This work shows that, as in Utopia Planitia, sublimation of interstitial ice is a likely process explaining the formation of the scalloped depressions in the region of Peneus/Amphitrites Paterae. Therefore, we provide a simplified scallop formation model based on sublimation of interstitial ice as proposed for Utopia Planitia. We also show that the differences in scallop morphologies between the two regions may be explained by differences in near-surface ice content, sublimation rates and age of formation of the scalloped terrains.

1. Introduction

The Peneus and Amphitrites Paterae region, just south of the Hellas Basin (Fig. 1), displays a high concentration of polygonal terrains and scallop-shaped depressions reminiscent of periglacial landscapes on Earth (Plescia, 2003; Lefort et al., 2005; Lefort, 2008; Zanetti et al., 2008). Scallop-shaped depressions (or "scallops") have been previously observed in various areas of the martian mid-latitudes, with a northern concentration in Utopia Planitia (e.g. Costard and Kargel, 1995; Plescia, 2003; Morgenstern et al., 2007; Soare et al., 2007; Costard et al., 2008; Lefort, 2008; Lefort et al., 2009).

Scallops form within smooth areas of mantling terrains, in material which may be the remnants of an ice-rich mid-latitude mantle that still covers the martian surface between ~30° and 60° latitude. These mantling deposits are postulated to be made of ground ice–cemented dust with unknown relative proportions of dust and ice (e.g. Mustard et al., 2001; Kreslavsky and Head, 2002; Head et al., 2003). They may have formed by transport of ice from polar reservoirs, followed by airfall deposition in mid to high latitudes during periods of high obliquity less than 5 Ma ago; after a return to lower obliquity (including the present), the ice-rich mantle would progressively become eroded from lower to higher latitudes (e.g., Mustard et al., 2001; Head et al., 2003; Milliken and Mustard, 2003; Milliken et al., 2003), much as the Earth's annual orbital progression affects seasonal snow cover on Earth. Alternatively, more recent GCM results of Levrard et al. (2004) and Madeleine et al. (2007) predict that as obliquity decreases from high values ($\geqslant 45°$), low-latitude ice deposits become unstable and are redeposited in the mid-latitudes as an ice–dust mantle. This mid-latitude ice then sublimates and is transported poleward by the atmosphere as obliquity decreases further. In either case, the latter, erosional stage appears to describe the present situation. We use the term "ground ice" or "interstitial ice" to refer to the icy component of the ice–cemented mantle, without

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doi:10.1016/j.icarus.2009.06.005

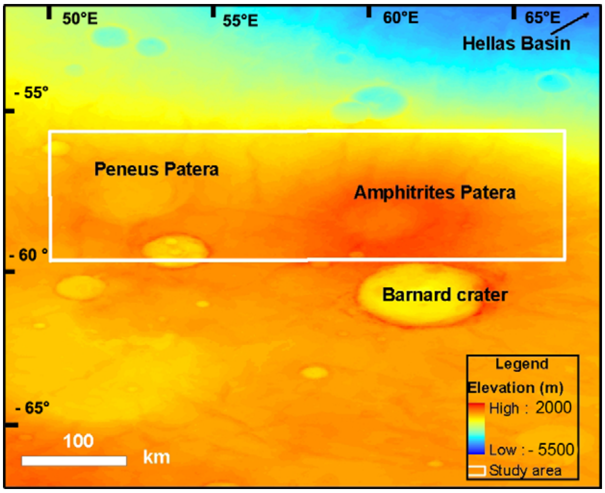

Fig. 1. Location of the study area, covering Peneus and Amphitrites Paterae on the southern rim of Hellas Basin. Color-coded MOLA topography is shown. Box bounds are 56–59.5°S and 50–66.5°E.

presuming any particular proportion of ice relative to the dust component.

The presence of ground ice at mid-latitudes is inferred from observation by the Gamma Ray Spectrometer (GRS) experiment on Mars Odyssey, from ice-stability models, and from geomorphological observations. In 2002, GRS data, which are directly dependent on the concentrations of hydrogen, and therefore almost certainly upon the concentration of water, within roughly one meter of the surface, showed the presence of extensive ground ice within this upper meter above ~50° latitude in both hemispheres (Feldman et al., 2002; Boynton et al., 2002; Mitrofanov et al., 2002); concentrations typically range from ~2 to 5 wt% at ~40° latitude to ~20 wt% at 60° latitude, generally increasing polewards (Feldman et al., 2004). Ice-stability models, which are consistent with the GRS observations, show that ground ice within a meter, or less, of the surface should generally be stable above 45–55° latitude (e.g., Mellon and Jakosky, 1993; Allen and Kanner, 2007). At the same latitudes, landforms possibly as young as one million years old have been interpreted as evidence of recent localized reworking of the martian surface by the action of near-surface ground ice (Malin and Edgett, 2000; Baker, 2001; Mustard et al., 2001). Direct evidence of the presence of ground ice at high latitudes (68.22°N) on Mars has been provided by the Phoenix lander (Arvidson et al., 2008), which found widespread icy soil only a few centimeters below the surface, under a desiccated layer of soil (Smith, 2009). Although this ice was found at high latitude, its presence reinforces the possibility of the existence of similar ice-rich ground in the mid-latitudes, possibly in lower amounts and/or at a greater depth.

The depth and ice content of the mid-latitude ground-ice deposits is still subject to debate. The Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS, several-km penetration depth) and the Shallow Subsurface Radar (SHARAD, up to ~1 km penetration depth) (e.g., Phillips et al., 2007; Plaut et al., 2007) have not yet found clear evidence for widespread, thick layers of ice or ice-rich material above 50° latitude, in the areas where hydrogen has been found by GRS. This suggests that either the ice-rich zone is less than a kilometer thick, or that the amount of ice within the ground is not sufficient to be detected by the radars. GCM results of Levrard et al. (2004) predict deposition of ~10 m of water ice at mid-latitudes as obliquity decreases from high values (⩾45°) and equatorial ice deposits become unstable. According to this model, the thickness of the ice-rich deposits at mid-latitudes should be larger than 1 m and no more than a 100 m.

Scalloped depressions, present in latitudinal bands centered at roughly 47°N and 55°S in their respective hemispheres, are consistent with the ice–cemented mantle hypotheses and, by their morphology, point to an erosion process involving sublimation driven by insolation. They may also mark the current zone of maximum mantle degradation, an erosion process which, possibly, could still be active today. The region is also covered by polygonal cracks similar to Earth permafrost polygons (as previously observed by Mellon, 1997; Seibert and Kargel, 2001; Mangold, 2005). On Earth, polygonal terrains are most often networks of thermal contraction cracks which form in polar or alpine regions because of seasonal to annual contraction of the permanently frozen ground (Lachenbruch, 1962; French, 2007), although other processes, such as desiccation, can produce similar patterns. Their presence is another clue to the presence of ground ice within the scalloped terrains, although it does not constitute a proof in itself.

The hypothesis that ground-ice sublimation could lead to scallop formation was proposed by Plescia (2003) based on analysis of images from the Mars Orbiter Camera (MOC). We and other authors have expanded this view by analysis of scalloped depressions in the region of Utopia Planitia (Morgenstern et al., 2007; Soare et al., 2007; Costard et al., 2008; Lefort, 2008; Lefort et al., 2009). The present work follows our study of Utopia Planitia (Lefort et al., 2009) using HiRISE data (McEwen et al., 2007) of similarly scalloped depressions and associated periglacial features in Peneus/Amphitrites Paterae. We included HiRISE images at 11 sites within the range of 56–59°S and 50–65°E, including three with stereo coverage. Although the HiRISE images cover only about 1% of the study area, they are well spread out over the whole study area and show similar small-scale features, which appear representative of the scalloped depressions of that area. Images from MOC and from the Thermal Emission Imaging System (THEMIS) were also used as context images. Observation made with these instruments on the scalloped terrains, although at a lower resolution, are consistent with HiRISE observations. By characterizing this region and comparing it with Utopia Planitia we deepen our understanding of these unusual features and their possible role in the volatile and erosion cycles of Mars.

2. Study area

Peneus and Amphitrites Paterae (Fig. 1) are two low-relief circular calderas at a mean altitude of 1000 m and have been interpreted as basaltic volcanic constructs (Plescia, 2003). In this region, the mantling terrains cover the high plains and fill craters less than 15 km in diameter. Craters up to 1 km in diameter are almost totally buried, which, suggests a mantle thickness of several tenths of meters (Plescia, 2003). The GRS indicates the presence of ~6 to ⩾20 wt% water ice within the first meter of the surface (Feldman et al., 2004) and ice-stability models (e.g., Mellon et al., 2004) show that ground ice should be stable below a depth of tens of centimeters. Although there is no direct evidence for the presence of ground-ice concentrations higher than those given by GRS at depths greater than one meter below the surface, the results from the ice-stability models (e.g., Mellon and Jakosky, 1995; Mellon et al., 2004) and martian global climate models (e.g., Levrard et al., 2004) suggest that it is plausible that ice concentrations are higher at depth, or were higher at depth in the recent history of Mars, a condition that is essential to the formation of periglacial landforms. Additional observations such as patterned ground (e.g. Mangold, 2005), and viscous creep features (e.g. Mustard et al., 2001), may be consistent with the presence of relatively high concentrations of ground ice in this region. Moreover, this region is within the boundary zone of 50–60°S where the GRS-derived concentration of ground ice in the near-surface suddenly increases from ~3 wt% to ⩾20 wt% within a global band of ~10° latitude (Feldman et al., 2004), which makes it a particularly likely area in which landforms may have been formed or shaped by ground-ice degradation. The TES albedo value of 0.16 indicates that relatively little dust is present on the surface (Fergason et al., 2006).

3. Geomorphology of the scalloped terrains

3.1. Scalloped depressions

As in Utopia Planitia (e.g., Soare et al., 2007; Morgenstern et al., 2007; Costard et al., 2008; Lefort, 2008; Lefort et al., 2009) scalloped depressions in Peneus/Amphitrites Paterae range in shape from elongated to almost circular, are rimless and shallow, a few tens of meters deep and a few hundred meters to a few kilometers across (Fig. 2). We use the terms “scallop floor” to refer to the inside of the scallops and “upper surface” to refer to the higher surface within which the scallops form. Some depressions have apparently coalesced together, leading to the formation of kilometers-wide regions of broadly and heavily pitted terrain. Within scallops, pole-facing slopes are usually steep scarps while equator-facing slopes are less steeply sloping. Topographic profiles from the Mars Orbiter Laser Altimeter (MOLA) on Mars Global Surveyor (surface spot size of ~150 m, with along-track shot spacing of ~300 m; Smith et al., 2001) indicate that the polar-facing slope is ~15°, while the equator-facing slope is ~5°. However, HiRISE images and stereo pairs suggest that the pole-facing scarp is often steeper. The absence of shadows on east-facing scarps indicate that the scarps are ~35° or less, which is similar to the steepness of the scarps in Utopia Planitia (Lefort, 2008; Lefort et al., 2009). Unlike the floors of Utopia Planitia scallops, Peneus/Amphitrites scallop floors display no large, scallop-scale, scarp-parallel, blunt ridges but often contain many, scattered, much smaller, sharper curvilinear ridges with pole-facing scarps and a gentler equator-facing sides (Fig. 3). Such curvilinear ridges are also sometimes present on surrounding smooth terrain along with small, possibly incipient, scallops. The scalloped depressions form within parts of the mantling terrains which are typically located on gentle (~4° according to MOLA) north-facing slopes (Fig. 4). Flatter terrain at the top and bottom of these slopes is generally pitted, apparently corresponding to a more advanced stage of erosion of the deposits. This pattern was not observed in Utopia Planitia where the scalloped depressions formed on terrains of variable slope orientation (Lefort et al., 2009).

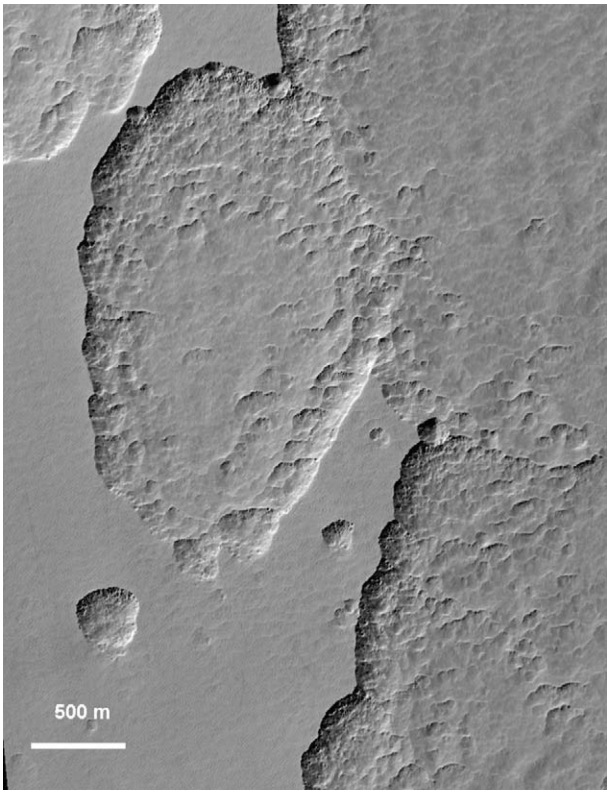

Fig. 2. Scalloped terrain in Peneus Patera. Scallops are oval to scalloped-shaped depressions. They typically have a steep pole-facing scarp and a gentler equator-facing slope. Floors often host many small curvilinear ridges with this same sense of asymmetry. Large areas of knobby terrains probably originate form the coalescing of several scallops (north is up and illumination is from the left in all figures unless otherwise noted; PSP_005698_1225, −57.0, 51.3°E, Ls = 330.6°).

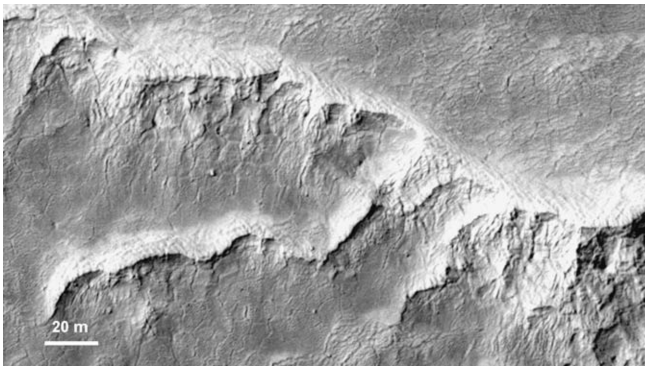

Fig. 3. Small asymmetrical ridges on a scallop floor, similar to those scattered over the scallops in Fig. 2. The pole-facing sides of these ridges are steeper than the equator-facing side (PSP_4340_1235, −56.2°, 50.2°E, Ls = 267.6°, Sun from upper left).

In several locations over the study area are roughly circular features several kilometers across and displaying a central, roughly circular, smooth terrain surrounded by a ring of lower pitted terrain, itself surrounded by another ring of smoother terrain, likely corresponding to degraded craters (Fig. 5). As opposed to Utopia Planitia, the smooth upper surface within the study area is mostly devoid of boulders. A few clusters of angular boulders, up to 4.5 m across, exist and are generally relegated to degraded parts of the mantle. Some of the boulders appear to have fallen down the scallop scarp, supporting upslope tails of fine material (Fig. 6). As in Utopia Planitia, the color of these terrains is relatively uniform with some redder areas where dust has accumulated. In some images, the pole-facing scarps display very bright deposits, probably CO_2 or H_2O frost deposits (Fig. 7a). More sparse frost deposits are also visible inside polygon troughs (Fig. 7b). THEMIS brightness-temperature maps show that the temperature is a few degrees warmer on the equatorial-facing slope of the scallops, which is in accordance with the observation of frost deposits on the scarps and with expected patterns of insolation.

3.2. Basketball terrains, polygons and circular pits

The upper surface near the scallops is smooth at large scale. However, a closer look shows a regular hummocky surface (Fig. 8) with individual hummocks typically 10–30 m across. This terrain recalls the “basketball terrain” identified at high northern latitudes, particularly above 60°N (e.g., Kreslavsky and Head, 2002; Head et al., 2003). However, the southern basketball knobs apparently lack the central concentrations of boulders that comprise the northern basketball terrain. An overlying network of small polygons and narrow cracks also overlie the upper surface

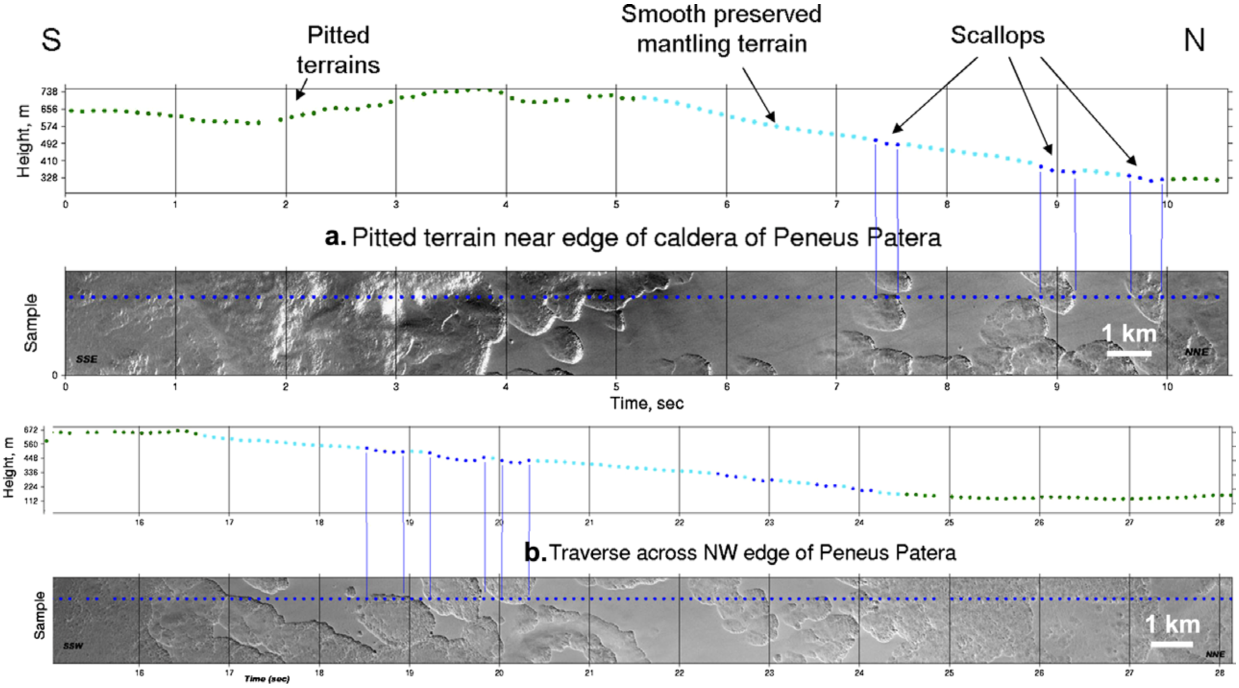

Fig. 4. MOLA topographic profiles over several scalloped depressions. (a) Top: MOC image M0402521, 57.60°S, 54.29°E, Ls = 192.59, illumination is from the top left. (b) Bottom: MOC image M0706070, −57.27N, 51.33E, Ls = 216.05, illumination is from the top. Light blue segments represent smooth, preserved upper surfaces, dark blue segments represent scallops, green segments represent pitted terrains. Remnants of the mantling terrain and scallops are generally located on equator-facing slopes while pitted terrains are located on flat or pole-facing slopes, implying that the mantling terrain has been better preserved until the present on equator-facing slopes.

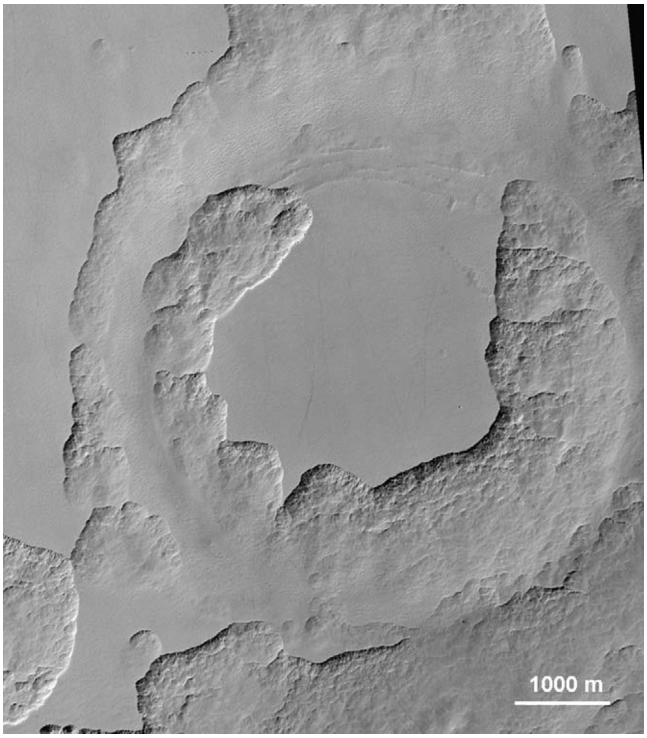

Fig. 5. Circular feature, likely a degraded crater. This ancient crater was probably filled by the layer of smooth material. Erosion of this material subsequently followed the crater rim, leaving the circular pattern (PSP_005698_1225, −57.0, 51.3°E, Ls = 330.6°).

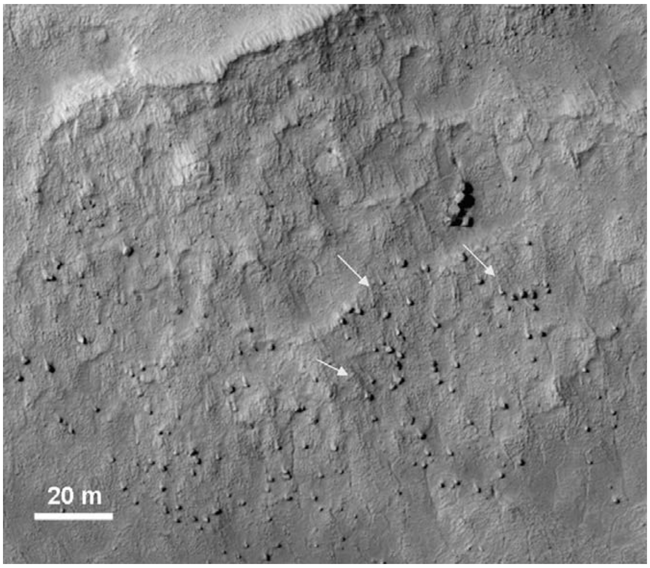

Fig. 6. Fallen boulders on a scallop slope. Boulders are up to 4 m across. Arrows point to some of the upslope tails of finer material collected behind the blocks (PSP_005698_1225, −57.0, 51.3°E, Ls = 330.6°, Sun from upper left).

and the scallop floor. In Utopia Planitia the polygons on the upper surface, on the scarp and on the scallop floor have different sizes and shapes, but here in the south the appearance and size of the polygon network is similar over these different areas of the scalloped terrain (Fig. 9a). These polygons are less than 10 m wide and most of them are hexagonal with angular intersections of ∼120° and troughs about 1 m wide. At the top and in the middle of some scarps are fractures that seem to correspond to an enlargement of a polygon trough (Fig. 9b). Widening cracks may lead to eventual failure and detachment of the edge section, a process that likely contributes to scarp erosion and may be the origin of some of the scarp blocks. The parts of the polygon network which overlie the scarps are highly disturbed by pits, ranging from a few meters

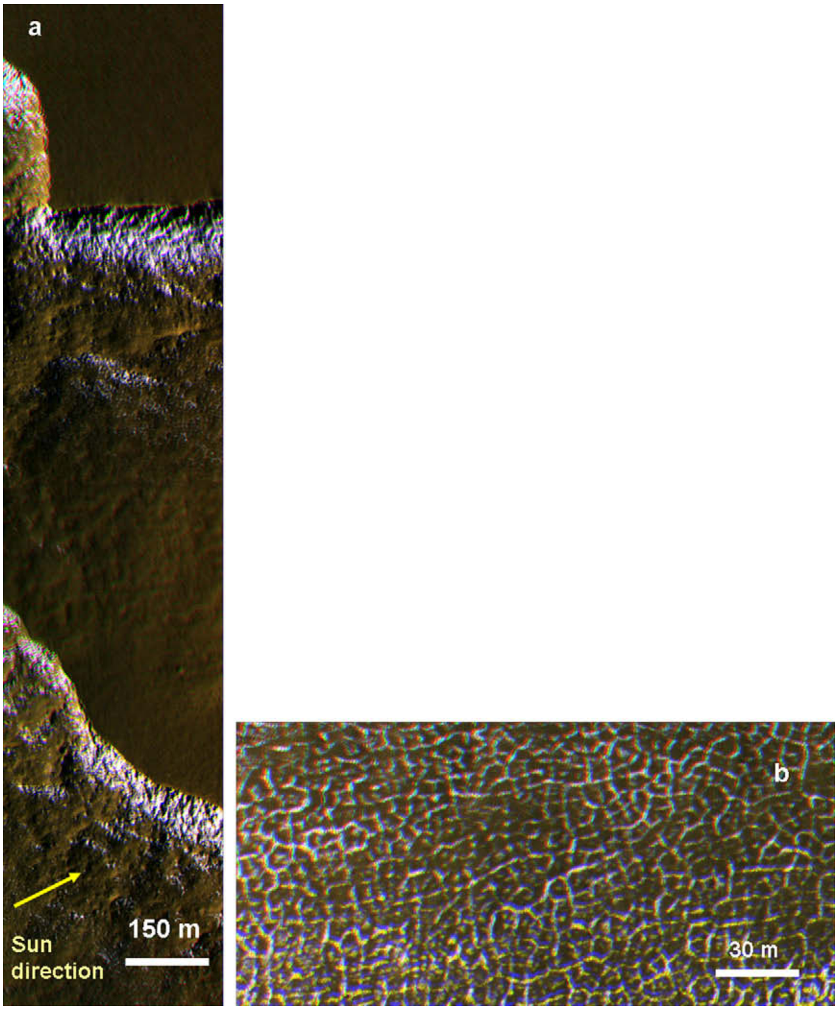

Fig. 7. (a) Frost cover on pole-facing scarps. (b) Frost within polygon cracks (PSP_002731_1210, −58.6, 50.2°E, Ls = 190.0°).

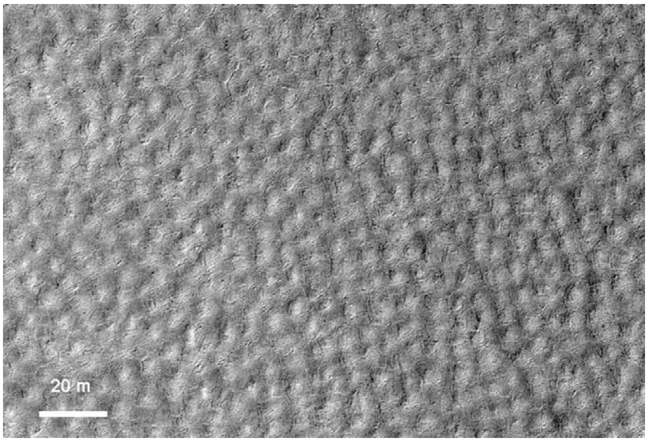

Fig. 8. Upper layer with regular, bumpy texture similar to "basketball terrain" (PSP_004340_1235, −56.2°, 50.2°E, Ls = 267.6°, illumination is from the lower left corner).

to several tens of meters across (Fig. 9a and c). These pits are circular, wide at the top and narrowing downward, resembling an inverted cone. They seem to evolve from local enlargement of polygon troughs, especially at trough intersections. Pits such as these are not observed on scallop scarps in Utopia Planitia.

Table 1 summarizes the similarities and differences between the scalloped terrains in Peneus/Amphitrites Patera and in Utopia Planitia.

4. Scallop formation process

The GRS measurements of water ice content (~6 to ⩾20 wt%, Feldman et al., 2004) are similar to values suggested by ice-stability models (⩾10%, Mellon and Jakosky, 1993; Allen and Kanner, 2007). Moreover, this area may be able to support liquid water conditions for about 10% of the martian year when taking into account insolation and pressure factors (Lobitz et al., 2001); other estimates are lower, e.g., ~2% (Haberle et al., 2001). However, while sufficient environmental conditions include the potential for the involvement of a solid–liquid phase change in morphological change on Mars during brief annual periods, it is difficult to prevent the depletion of an ice deposit by sublimation of ice directly into the gas phase, as temperatures rise, before the melting point can be reached (Hecht, 2002). Furthermore, climate and ground-ice models (e.g., Mellon and Jakosky, 1995; Levrard et al., 2004) do not predict sustained stability of liquid water given the orbital constraints of the last ~20 Ma (Laskar et al., 2004) whereas these same models do predict significant latitudinal fluctuations of solid–gas equilibrium relationships over this same time period, especially around the latitude of scalloped depressions. While the age of the scallops is unknown, in Utopia they are presumed to

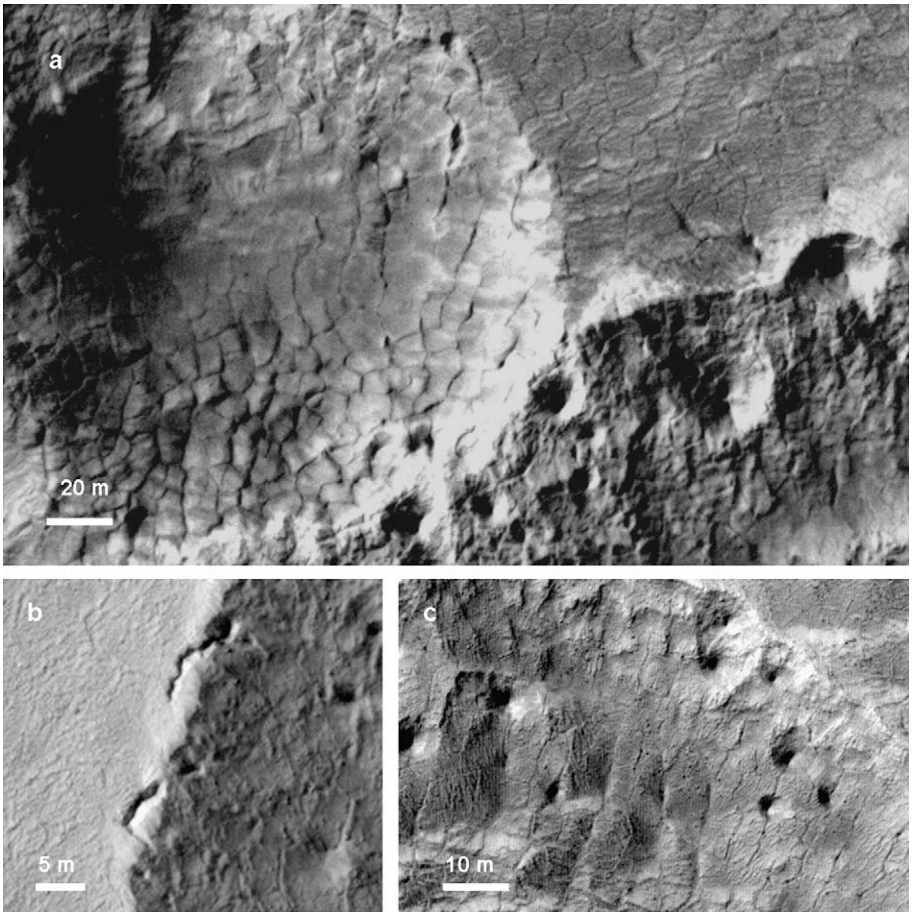

Fig. 9. (a) Polygons on the upper surface and scallop scarp; large pits on the scallop scarp. (b) Crack enlargement at the top of a scarp. (c) Pits on the scarp within cracks (PSP_004340_1235, -56.2°, 50.2°E, Ls = 267.6°, Sun from left).

be as young or younger than some crater-wall gullies (Soare et al., 2007). Under current and recent climate conditions, then, there is a high likelihood, and good independent evidence (e.g., Mustard et al., 2001; Milliken et al., 2003; Milliken and Mustard, 2003; Kreslavsky and Head, 2002; Head et al., 2003), that sublimation has had some effect on such mantling terrains with similar appearance and at the same latitudes as the scallops. We find the scalloped terrains, also, to be indicators that such sublimation has occurred within an ice-rich mantle (discussed further below; e.g., Lefort et al., 2009), consistent with independently theorized and observed regional history.

Just because the models above do not predict the possibility for sustained, ponding water yet do predict conditions consistent with a range of observed sublimation morphologies at mid-latitudes (e.g. Milliken et al., 2003), does not completely rule out the possibility that scallops could be the dry remnants of thermokarst lakes (representing the second major hypothesis for scallop formation; e.g., Soare et al., 2007, 2008; Costard and Kargel, 1995). Likewise, the resemblance of several features of terrestrial thermokarst lakes to scallops raises the possibility that liquid water was involved, but does not require it. We find no geomorphic evidence requiring the sustained presence of liquid water in the formation of scallops. Rather, the morphology of the scallops recently revealed by HiRISE images, stereo pairs, and a digital elevation model (in Utopia Planitia; Lefort et al., 2009), speaks against a defining role for melting or standing water, e.g. as in a thermokarst lake scenario. A typical characteristic of scallops is that while portions of the scarp edge, or lip, are distinct, there is never a raised rim, similar to terrestrial thermokarst lake or alas morphology (Soare et al., 2007, 2008; Costard and Kargel, 1995). HiRISE data reveals that these depression-lips, however, commonly do not maintain a constant elevation around their perimeter, and thus could never have been filled evenly to the brim. A lake contained in the low part of the scallop, not inconsistent with non-uniform depression-lip heights, might be expected to leave a terrace or shoreline. In Peneus/Amphitrites Peterae, evidence of such features are absent; in Utopia, where the broad, scarp-parallel ridges have been proposed to be just such features (Soare et al., 2007, 2008; Costard and Kargel, 1995), HiRISE relief shows that these ridges, also, do not always maintain a constant elevation along their length, nor are they always at successively decreasing elevations as they might be if reflecting successive lake levels or horizontal layering within the mantling deposit (Lefort et al., 2009). Finally, regardless of the presence of ridges, locally high-standing or sloped surfaces that are heavily pocked with coalesced, scallop-like depressions of which the downslope side is open (existing in Utopia and Peneus/Amphitrites Paterae) present a landscape incapable of confining liquid within the incised scarps.

In spite of differences in the smaller-scale morphology, the general morphology of the scallops in Peneus/Amphitrites Paterae is very similar to that of the scallops of Utopia Planitia: depressions in both hemispheres have similar but mirrored morphologies (i.e., most of the steeper scarps are pole-facing, with few exceptions that are equator-facing) As in Utopia Planitia, the asymmetrical morphology of these scallops and their latitude-dependent distribution (Milliken and Mustard, 2003) point to a scallop formation process controlled by climatic and insolation factors. Therefore, we consider it most likely that the formation process of

Table 1
Comparision between the scalloped terrains in the region of Peneus-Amphitrites Patera and the scalloped terrains in Utopia Planitia.

	Peneus/Amphitrites Patera	Utopia Planitia
Latitude	$\sim$55°S	$\sim$45°N
Mean elevation	1000 m	−4500 m
Regional slope	$\sim$4° regional equator-facing slope	Relatively flat terrain
Material	Very dusty and high density of boulders	Fewer dust and boulders
Scallop morphology		
Shape	Elongated in north–south direction	
Base profile	The elevations of the base of the scallops increase poleward	
Slope profile	Equator-facing slope = steep scarp $\sim$15–30° Pole-facing slope = gentle slope $\sim$2–5°	
Depth	$\sim$5 to 25 m	
Extend of a single scallop (non-coalescing)	A few tens of meters to $\sim$2–3 km	
Features left by coalescing scallops	Areas of fretted of hummocky terrains Ridges between coalescing scallops	
Interior features	Small straight ridges	Large curvilinear ridges
Features on the scarp	Small polygons, promontories	Small polygons, circular pits, boulders
Polygons		
Network type	Homogeneous	Heterogeneous. Mostly large polygons, with smaller polygons on the scarp of the scallops
Size	$\sim$10 m across	Small polygon network: 5–10 m across Large polygon network: 30–150 m across
Trough width	$\sim$1 m	Small polygon network: $\sim$0.5–1 m across Large polygon network: 30–150 m across

these scalloped depressions is similar to the formation process proposed for the scallops in Utopia Planitia (e.g. Lefort et al., 2009). This process is also consistent with the formation process proposed by Plescia (2003), Lefort et al. (2005), and Zanetti et al. (2008) for the Peneus/Amphitrites Paterae region. In this model, ice-rich terrains overlain by a relatively thin, desiccated, dusty layer undergo slow sublimation within ground irregularities, such as small depressions, where ice may be relatively closer to the surface (Fig. 10, stage 1). This induces a collapse of the dusty material resulting in a small primary pit, or a very small scallop (Fig. 10, from stage 2). These pits enlarge progressively poleward because of enhanced insolation and ground-ice sublimation on the equator-facing slope.

Initiation of scallops from ground irregularities by ground-ice sublimation has been proposed by Plescia (2003) based on the analysis of MOC images. However, the pixel scale of these images did not resolve these ground irregularities. HiRISE gives us insight into the early stage of scallop development and enables us to see the ground irregularities postulated by Plescia (2003). Two types may be observed: the first corresponds to a wavy regular pattern of subtle ridges, troughs and knobs similar in form to small dunes or hummocks (Fig. 10, stage 1); the second is a series of small faults and pits (Lefort, 2008; Zanetti et al., 2008). In both cases, the scallops extend in a poleward direction. However, in the case of the wavy terrain, young scallops (Fig. 10, stages 2–4) are wider and more circular, while in the case of the faults, they start with a narrower, more elongate shape. Large scallops have the same elongated shape, independent of the type of pits from which they develop (Fig. 10, stages 5–7).

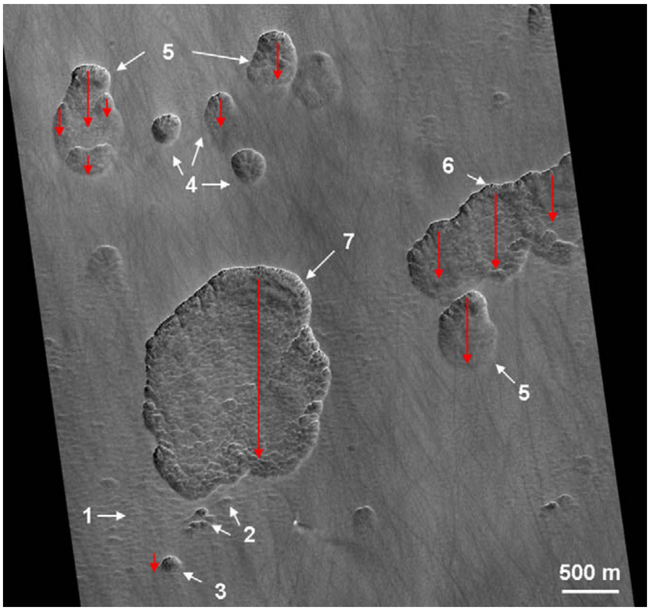

Fig. 10. Example of scallops evolution. This image show the evolution of scallops from small ground irregularities to progressively larger elongated depressions. This erosional process occurs first by development of small pits (1) that extend poleward by sublimation of near-surface ice (2–7). Red arrows indicate the main general direction of scallop extension. Several of these depressions may coalesce (6). On this image, scallop initiate from a wavy, hummocky-typed surface and the young scallops (2–4) are relatively wide and circular, while more developed, larger scallops have a more elongated shape (7). A dust devil appears just below the largest scallop: the bright cloudy feature is consistent with a vertical, roughly columnar form, casting a shadow directly opposite the Sun direction and trailing a thin cloud to the southeast, consistent with the dominant north–south trend of dust-devil tracks covering the image. (PSP_004168_1220, -57.9°, 65.5°E, Ls = 259.1°, Sun-direction 290° clockwise from up).

Temperatures are colder on the pole-facing scarp of the scallops, as shown by THEMIS temperature maps and by the deposits of frost observed on HiRISE color images. By raising the albedo of the slope, these deposits probably also contribute to lowering of the surface temperature. Near-surface ice may be preserved there in greater amounts and act as a cementing agent that stabilizes the steeper scarp, although localized sublimation may still occur within polygon fractures and pits. The presence of boulders on the scarp and buildup of finer material on their upslope surfaces suggests that gravity also plays a part in the evolution of the scarp. Although there are not enough boulders and material deposited at the foot of the scarp for mass-wasting to be considered the main erosional process, a combination of localized, low-volume mass-wasting and sublimation through small fractures may give the scarp its steeper and cracked and pitted appearance. The notable circular, conical pits on the scarps may form by intense, localized sublimation of interstitial ice within a polygon crack intersection where the ground ice has been provided a relatively unobstructed path to the atmosphere.

Eventually, nearby scallops coalesce together (Fig. 10, stage 6), often exhibiting zones of low curvilinear ridges and accompanying hollows (Figs. 2 and 3). Small scarps and curvilinear ridges on the scallop floor may be aborted remnants of incipient scallop formation, starting points of new scallops, or a scallop-like erosional form developing on a smaller scale. As in Utopia Planitia, aeolian erosion is expected to assist scallop formation by removing desiccated material accumulated in the scallops after removal of the icy component. As proposed by Zanetti et al. (2008), the slopes of Hellas basin may cause wind gradients that are strong enough to remove the accumulated desiccated layer. Dust devils are also implicated by the many tracks in the region and evidenced directly by one captured in action in the lower part of Fig. 10.

According to Plescia (2003), scallop formation could be ongoing at the present time, however, comparison of overlapping HiRISE and MOC images acquired ~5 years apart (Fig. 11), does not reveal any change in the small-scale scallop morphology at MOC resolution (e.g. ~2.8 m in Fig. 11). As in Utopia Planitia, our observations suggest that either the scallops are not currently undergoing any modification, or that modifications have occurred at a slow, subpixel scale during the past 5 years.

The hexagonal shape of the polygonal cracks suggests homogeneity of the subsurface and a uniform cooling rate of the ground in winter (Lachenbruch, 1962; Mellon, 1997; Mangold, 2005; French, 2007). Moreover, the homogeneity of the polygon sizes over the whole mantle deposits also points to simultaneous formation in a subsurface with homogeneous ice content. These findings are unlike those for Utopia Planitia, where the inhomogeneity of the polygon network suggests variations in the near-surface ice concentration over a scallop, some areas of the Utopia Planitia scallop terrains being possibly more desiccated than others (Lefort, 2008; Lefort et al., 2009). This may also explain why there are no large ridges on the scallop floor as in Utopia Planitia. Ridges may form by mass-wasting after a period of sublimation and accompanying loss of cohesion of scarp material reduces the near-surface ice/dust ratio below a certain threshold (Lefort, 2008; Lefort et al., 2009). The fact that the polygon network in the Peneus/Amphitrites Paterae region is continuous and homogeneous over the upper surface, the scarp, and the polygon floor, also implies that the polygons either postdate the scallops or that they started forming after scallop formation was underway.

The erosion process leading to the formation of scallops seems to be influenced by the underlying structure of the ground. The roughly circular feature in Fig. 5 probably corresponds to an ancient crater, buried by the deposition of the smooth layer. The raised, central plateau corresponds to the remnants of the layer filling the crater, while the smooth ring corresponds to the crater rim. The intervening terrain is degraded to the east, south, and west, bounded by relatively steep scarps with the central remnant and by gentle slopes toward the surrounding rim. More minor curvilinear ridges common within this degraded partial annulus have pole-facing scarps, as do those within scallops. To the north, a smooth connection exists between the central and the rimming material, interrupted not by degraded terrain but only by a few relatively narrow, shallow troughs paralleling the rim. These troughs may indicate the type of initial irregularity from which degradation expanded, but the generally coherent, continuous mantle here in the north, in spite of the trough presence, underscores the azimuthal influence on erosion. The asymmetric pattern of partial-annulus erosion within the crater, the asymmetry in bounding scarps, and the exclusively pole-facing orientation of minor interior scarps recall the morphologies and asymmetries characteristic of scallops, suggesting that the same, or a similarly influenced, erosion process was active here. However, this process has been influenced by the presence of the crater and, instead of forming typical scallops, erosion has progressed following the structure of the underlying crater. This implies that the scallop shape is adopted within the mantle deposits when there are no constraints but that the pre-existence of a structural shape, with particular topography and material resistance, can control the pattern of erosion, probably by influencing the amount of insolation received by surfaces in different areas, the degree of compaction of the deposits, and/or the propagation of erosion due to subsurface relief structure.

The presence of boulders in deposits postulated to have been deposited by atmospheric processes may seem paradoxical, and their origin is still being debated. Only few boulders are scattered over the study area and there is no indication of a higher density of boulders on the scallop floor than on the upper surface. Several of these boulders appear to have fallen from the top of the scallop scarp. Therefore, it is likely that boulders are concentrated at the

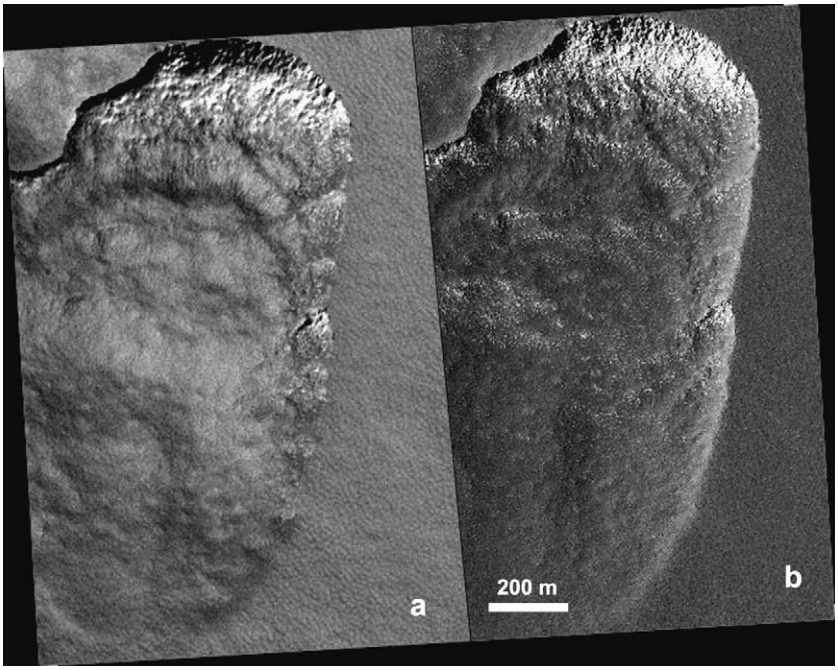

Fig. 11. Comparison between (a) MOC image M0706070 (−57.27°, 51.33E, Ls = 216.05, scale: 5.5 m/pixel), acquired on the 30 September, 1999, and (b) HiRISE image PSP_005698_1225 (−57.0°, 51.3°E, Ls = 330.6°, scale: 0.25 m/pixel), acquired on the 14 October, 2007. We do not observe any change at the MOC resolution of 5.5 m/pixel.

surface, which implies that they have been superposed later on the ice-rich deposits. Current proposed hypotheses for the presence these boulders include crater ejecta, ancient ejecta blankets and induration of fine material (McEwen et al., 2007).

5. Origin of the differences between the scalloped terrains in Utopia Planitia and in Peneus/Amphitrites Patera

The morphological differences between scallops in Peneus/Amphitrites Patera and Utopia Planitia may be explainable by differences in hemispherical location, latitude, elevation and ground-ice content of each region, which influence sublimation rates. Due to Mars' current season of perihelion, southern summers are warmer, although shorter, than northern summers. All else being equal, these conditions and the slightly higher latitude of the Peneus/Amphitrites Patera study region (centered at ~55°S) should lead to a lower average yearly temperature but a higher peak summer temperature than in the Utopia Planitia scalloped region (centered at ~47°N). The higher elevation of Peneus/Amphitrites Patera (by ~ 6 km) should also promote relatively higher sublimation rates. While these factors have an impact on sublimation rates, their relative and net influences are difficult to quantify over changing orbital parameters. For all these assumptions, we consider that the dust/ice ratio and the ice depth are similar in both regions. However, as shown by GRS, the near-surface ice concentrations are actually very different: the quantity of hydrogen in the upper ground in western Utopia Planitia is equivalent to only ~4 wt% ice, while it is ~6 to $\geqslant$20 wt% in Peneus/Amphitrites Patera (Feldman et al., 2004). Such a difference could result from the latitudes of each region. As the Peneus/Amphitrites Patera region is located at higher latitude than the scalloped Utopia Planitia region, the net, pre-erosion amount of ice deposited (over several cycles of equinox precession) may have been higher. Moreover, considering the hypothesis that the mid-latitude mantle becomes unstable from lower to higher latitudes as the planet return from higher to lower obliquity, the mid-latitude mantle deposits in Utopia Planitia may have started to erode sooner than the deposits in Peneus/Amphitrites Patera. Most of the near-surface ice may have already sublimated, which would explain why GRS does not measure high concentrations of ice within the first meter of the ground. Ice degradation in Peneus/Amphitrites Patera may have been initiated more recently.

Differences between the two types of scallops may also be explained by the hypothesis that scallops in Utopia Planitia are older than those in Peneus/Amphitrites Patera and were formed in an originally less ice-rich, thinner mantle deposit. The ice-rich deposits could have been emplaced at about the same period but the scallops of Utopia Planitia may represent an older period of erosion while the scallops in Peneus/Amphitrites Patera represent a more recent, possibly current, period of erosion. This would explain why the landforms of Utopia Planitia appear more desiccated than the landforms in Peneus/Amphitrites Patera. It may also explain the appearance of the polygons in each area. Indeed, polygons on the upper surface in Utopia Planitia are larger and possibly more evolved than the smaller polygons in Peneus/Amphitrites Patera. The scalloped terrains in Utopia Planitia may now be mostly desiccated, although the small polygons on and near the pole-facing scarp in Utopia Planitia may indicate areas protected from the Sun where the concentration of residual near-surface ice is higher. Such localized ice-rich areas could not be detected at GRS spatial resolution. In Peneus/Amphitrites Patera, the homogeneity of the polygon network may reflect higher and more homogeneous near-surface ice content and less evolved landforms. The reason for the absence of broad ridges inside of the scallops in Peneus/Amphitrites Patera may be that the cohesion of the material is higher, or the erosion more uniform, because of a higher ice/dust ratio. Another possibility, consistent with the Utopia Planitia scallops being older features, is that the internal ridges represent successive periods of sublimation and erosional activity (e.g., Lefort et al., 2009), of which the scallops in Peneus/Amphitrities Paterae have only experienced one. In summary, Utopia Planitia may present a more advanced stage of scallop evolution and mantle erosion than Peneus/Amphitrites Patera.

6. Conclusions

Periglacial-like landforms to the south of Hellas Planitia support the idea of recent degradation of a mid-latitude, ice-rich mantle. The morphology of the scalloped depressions in the Peneus/Amphitrites Paterae region is generally similar to the morphology of the Utopia Planitia scallops: shallow, elongated, rimless depressions with asymmetrical slopes steeper on the poleward facing side, gentler on the equator-ward facing side. As in Utopia Planitia, the overall morphology of the scalloped terrains suggests that the scalloped depressions are sublimation features. Their formation is controlled by differential insolation over pole- and equator-facing slopes. The presence of buried crater shapes shows that sublimation may be initiated or influenced by underlying topography. Notably, the similarities between crater-associated and independent scallop degradation reinforces several aspects of our formation model. This implies that scalloped depressions are a characteristic form resulting from sublimation of the mantling terrains in the absence of structural control. HiRISE images also reveal several previously unobserved details in the Peneus/Amphitrites Paterae terrains, such as the absence of the broad ridges present in Utopia Planitia, the uniformity in the length scales of polygons, the presence of fallen blocks and circular pits on the scarp, and the presence of a surface texture similar to the so-called, high-latitude "basketball" terrain. The fact that the hexagonal polygon network spans the scallop scarps indifferently, along with the absence of large ridges inside of the scallops, suggests that the ice-rich substrate is more homogeneous with less variations in ice concentrations over different areas of a scallop than in Utopia Planitia. Morphological differences between the two regions of scalloped terrains may be mostly explained by difference in latitude which in turn affects the local period and duration of mantle deposition and scallop erosion. The scalloped terrains of Peneus/Amphitrites Patera may therefore be younger than those of Utopia Planitia.

Acknowledgments

We thank the people at the University of Arizona, the Jet Propulsion Laboratory, Ball Aerospace and Lockheed Martin that built and operate the HiRISE camera. We also thank the people of the HiRISE Operations Center (HiROC) at the University of Arizona for acquiring and processing the HiRISE images used for this study. This work was funded by the Swiss National Science Foundation (SNSF).

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