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Hydrovolcanic features on Mars: Preliminary observations from the first Mars year of HiRISE imaging

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ABSTRACT

We provide an overview of features indicative of the interaction between water and lava and/or magma on Mars as seen by the High Resolution Imaging Science Experiment (HiRISE) camera during the Primary Science Phase of the *Mars Reconnaissance Orbiter* (MRO) mission. The ability to confidently resolve meter-scale features from orbit has been extremely useful in the study of the most pristine examples. In particular, HiRISE has allowed the documentation of previously undescribed features associated with phreatovolcanic cones (formed by the interaction of lava and groundwater) on rapidly emplaced flood lavas. These include "moats" and "wakes" that indicate that the lava crust was thin and mobile, respectively [Jaeger, W.L., Keszthelyi, L.P., McEwen, A.S., Dundas, C.M., Russel, P.S., 2007. Science 317, 1709–1711]. HiRISE has also discovered entablature-style jointing in lavas that is indicative of water-cooling [Milazzo, M.P., Keszthelyi, L.P., Jaeger, W.L., Rosiek, M., Mattson, S., Verba, C., Beyer, R.A., Geissler, P.E., McEwen, A.S., and the HiRISE Team, 2009. Geology 37, 171–174]. Other observations strongly support the idea of extensive volcanic mudflows (lahars). Evidence for other forms of hydrovolcanism, including glaciovolcanic interactions, is more equivocal. This is largely because most older and high-latitude terrains have been extensively modified, masking any earlier 1–10 m scale features. Much like terrestrial fieldwork, the prerequisite for making full use of HiRISE's capabilities is finding good outcrops.

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1. Introduction

NASA's Mars Exploration Program is centered around the theme of "Follow-the-Water" in hopes of identifying past, present, or future habitable locations in the quest for native life on Mars or future human endeavors on the Red Planet (MEPAG, 2008). Lava–water interactions provide a useful tool with which to sound for water in Mars' geologic past. This is because Mars' crust is fundamentally volcanic. Thus persistent bodies of surface or subsurface water would have had difficulty avoiding contact with lava or magma. We previously reported on initial HiRISE observations of primary volcanic features (Keszthelyi et al., 2008). Here we focus on the preliminary HiRISE investigation of features on Mars formed by volcano–water interaction (hydrovolcanism).

1.1. Overview of types of hydrovolcanism

On Earth, the encounter between lava and water produces a broad spectrum of distinctive features, depending on both the physical state of the water and the style of volcanism. Mafic lavas emplaced in liquid water commonly form pillow basalts, recognized by their oval cross-sections, thick glassy rinds, and paucity of vesicles (e.g., Fuller, 1932; Jones, 1968; Walker, 1971; Moore, 1975). At higher flow rates, subaqueous lavas can produce channelized and sheet flows (e.g., Griffiths and Fink, 1992; Gregg and Fink, 1995; Soule et al., 2005; Garry et al., 2006). In shallow water or along the margin of a body of liquid water the lava typically shatters, forming a glassy breccia called hyaloclastite that readily alters to palagonite (e.g., Carlisle, 1963; Bonatti, 1965; Fisher and Schminke, 1984). The hyaloclastite is commonly deposited in a delta with steeply dipping foreset beds (Jones and Nelson, 1970; Skilling, 1994). When the pile builds above the water level, regular subaerial lavas can form, only to flow into the water along the new coast to continue the production of hyaloclastite (and sometimes pillows) (e.g., Jones and Nelson, 1970; Kokelaar, 1986). When this process takes place in a subglacial environment, the volcanic edifice is called a moberg ridge if there is no capping subaerial flow, or tuya (a.k.a. table mountain) if capped by a layer of subaerial lava (e.g., Mathews, 1947; Jones, 1966, 1970). Volcanic eruptions, especially when pyroclastics entrain snow and ice, can trigger mudflows or debris flows, which are called "lahars" in the volcanological literature. On the low-energy end of the spectrum of hydrovolcanism, subaerial lavas that have undergone significant

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water-cooling often exhibit narrow columnar, curvicolumnar, or hackly jointing that is termed "entablature" (e.g., Tomkeieff, 1940; Long and Wood, 1986; Grossenbacher and McDuffie, 1995; Lyle, 2000).

Explosive lava–water interactions can form lava fountains and bubbles that deposit pyroclastic materials ranging from lithic bombs through spatter and lapilli to fine ash that build up littoral cones (e.g., Sheridan and Wohletz, 1983; Kokelaar, 1986; Mattox and Mangan, 1997). Similar explosions can take place with liquid lava interacting with groundwater or wet sediments, forming rootless cones (a.k.a. pseudocraters) (e.g., Thorarinsson, 1953; Fagents and Thordarson, 2007). If the interaction with sediments is less explosive, the mixture of glassy breccia and sediment is called a peperite (e.g., Skilling et al., 2002). At the most explosive end of the spectrum are maar craters and tuff rings where ascending magma interacts with groundwater to excavate large holes in the ground with very widely dispersed ejecta (e.g., Lorenz, 1973; Sheridan and Wohletz, 1983; Kokelaar, 1986).

This variety of processes can be broadly divided into there classes: (1) hydrovolcanism and hydromagmatism which is the most general term for lava–water and magma–water interactions, (2) phreatovolcanism and phreatomagmatism for interactions with groundwater, and (3) glaciovolcanism for lava–ice interactions.

1.2. Previous reports inferring hydrovolcanism on Mars

Essentially the full spectrum of hydrovolcanic features have been suggested, in one study or another, to exist on Mars. Perhaps most persistent have been reports of rootless cones, beginning with the 30–300 m/pixel images from the Viking Orbiters (e.g., Greeley and Theilig, 1978; Lucchitta, 1978; Allen, 1979; Frey et al., 1979, 1981; Frey and Jarosewich, 1982; Mouginis-Mark, 1985), continuing with $\geqslant$1.5 m/pixel Mars Orbiter Camera images (Lanagan et al., 2001; Greeley and Fagents, 2001; Bruno et al., 2004, 2006; Fagents and Thordarson, 2007; Baloga et al., 2007), and even the MER rover *Spirit* (Squyres et al., 2007). However, these same data have also led to a host of non-volcanic explanations (usually involving solely mud or ice) for different subsets of the potential phreatovolcanic constructs (PCs) (e.g., Tanaka et al., 2003; Farrand et al., 2005; Burr et al., 2005; Page and Murray, 2006). As reported by Jaeger et al. (2007), and summarized in Section 2.1, HiRISE confirmed a phreatovolcanic origin for the rings and mounds in Athabasca Valles.

The next most commonly reported features are tuyas (Hodges and Moore, 1978; Allen, 1979; Chapman and Tanaka, 2001; Gathan and Head, 2002; Smellie and Chapman, 2002; Chapman, 2003; Chapman and Smellie, 2007; Martínez-Alonso et al., submitted for publication). Tuyas are mentioned, in part, because enigmatic mesas are abundant across Mars. However, previous images did not resolve the hyaloclastite deltas or capping lava flows that would be diagnostic of tuyas. Similarly, enigmatic ridges seen in settings where both volcanism and glaciation are plausible are sometimes suggested to be Moberg ridges (e.g., Hodges and Moore, 1979; Chapman, 1994; Chapman et al., 2000; Smellie and Chapman, 2002; Head and Wilson, 2007). In similar locations, steep sided lava flows were suggested to have been stopped by now retreated glaciers (Gregg et al., 2007; Head and Wilson, 2007). 10–100 m scale images have also shown clear evidence for viscous flows on the flanks of Elysium Mons that have been interpreted as lahars (e.g., Mouginis-Mark, 1985; Christiansen, 1989; Russell and Head, 2003; Wilson and Mouginis-Mark, 2003). Again, while there were many strong suggestions that these flows involved the interaction between volcanism and icy sediments, the previous data did not resolve features diagnostic of a mudflow (as opposed to some other fluid, such as lava).

Features not suggested to be visible in previous images include pillow lavas and columnar jointing. This is simply because these features should require sub-meter spatial resolution, not because such features were not expected on Mars. Perhaps most perplexing was the lack of obvious maar craters or tuff rings. While such maars were suggested to be visible in north polar Viking images (e.g., Hodges and Moore, 1979; Zeitner, 1981), more recent studies have generally not supported this interpretation (e.g., Mitchell and Wilson, 1998; Garvin et al., 2000; Crumpler et al., 2007). Given the incontrovertible evidence for ground ice and volcanism on Mars, it seems that explosive interactions would be practically unavoidable. However, active aeolian and other modification processes may render maar craters indistinguishable from the ubiquitous degraded small impact craters (e.g., Crumpler et al., 2007).

1.3. Overview of HiRISE image data

The High Resolution Imaging Science Experiment (HiRISE) camera onboard the *Mars Reconnaissance Orbiter* (MRO) spacecraft provides unprecedented spatial scale (25–32 cm/pixel, depending on the altitude of the orbit). Meter-scale features are well-resolved by HiRISE, because of the very high signal-to-noise ratio as well as the pixel scale. Up to 14 separate charge-coupled device detectors are used for each observation to image a ~6-km-wide swath with the central 20% in enhanced color (McEwen et al., 2007a; McEwen et al., this issue). Meter scale topography is measured by stereogrammetry using images collected by rolling the spacecraft across track to view the same location on two different orbits (Jaeger et al., 2008; Kirk et al., 2008). Many of the figures in the online version of this paper are red–cyan anaglyphs constructed from such stereo pairs using the USGS Integrated Software for Imagers and Spectrometers version 3 (ISIS3) (Anderson et al., 2004; Becker et al., 2007). The combination of extremely high spatial resolution, color, and topography provide a panoramic view of the terrain that approaches that seen from Mars landers.

In the following we provide an overview of the HiRISE images of various possible hydrovolcanic and hydromagmatic features on Mars, beginning with the most definitive and moving to the more speculative.

2. Phreatovolcanic constructs, including rootless cones

2.1. Type examples from Athabasca Valles

The most pristine rootless cones imaged by HiRISE can be found in Athabasca Valles and were described by Jaeger et al. (2007). Athabasca Valles is generally thought to be the youngest "outflow" channel system on Mars (e.g., Tanaka, 1986), with a crater density indicating that it was resurfaced sometime between 1.5 and 200 Ma (McEwen et al., 2005; Jaeger et al., this issue). It starts at the Cerberus Fossae volcano–tectonic fissure system and extends 300 km to the southwest, debouching in the Cerberus Palus basin. The entire channel system was filled to overflowing by a voluminous flood lava that subsequently drained away, leaving a coating of lava only a few meters thick (Jaeger et al., 2007, this issue). This lava surface is dotted with thousands of "ring and mound landforms" that are shown to be phreatovolcanic constructs (a general term which includes rootless cones) (Jaeger et al., 2007).

Here we only briefly review the phreatovolcanic constructs (PCs) and associated features described in Jaeger et al. (2007). There are a number of key similarities between these structures and terrestrial rootless cones. For example, they are (a) found exclusively on the surfaces of lava flows and (b) overhanging cone walls are consistent with the expected strength of the welded spatter (Jaeger et al., 2007). Furthermore, the size range (1–100 m diameter) is similar to that of terrestrial rootless and littoral cones (e.g., Mattox and Mangan, 1997; Greeley and Fagents, 2001). Interestingly, the smaller cones are found preferentially along the margins of the flow and atop high topography (Fig. 1). We suggest two possible explanations for this observation. First, this may reflect the lower steam pressure underneath a thinner lava flow. Another process, which may be more important, focuses on the fact that the local flow duration would have been quite short at the margins and high stands of the lava flow. Therefore, in the areas with small PCs, only a relatively small amount of heat could have conducted into the substrate. The resulting small quantity of steam could only produce small explosions. This idea is supported by the numerical modeling by Greeley and Fagents (2001) which suggests that pyroclast ejection to $\sim$1 m would involve less than 1 kg of steam, while ejection to 20–50 m would require hundreds to thousands of kg of steam.

A highly unusual characteristic of the Athabasca PCs is that they often have moats that surround the cones and wakes that trail downstream (Fig. 2). Neither of these types of features has been reported associated with terrestrial rootless cones. Finally, the concentrations of PCs in Athabasca Valles are controlled by the underlying topography. The PCs are found preferentially along buried channel terraces and topographic highs in the substrate (Jaeger et al., 2007). This is most striking where cones demark the rim of impact craters that have been completely covered by the lava flow (Fig. 3). On Earth, rootless cones do not have such obvious correlation with substrate topography. Instead they show subtle clustering that can be discerned with well-chosen statistical analyses (Bruno et al., 2004, 2006).

Jaeger et al. (2007) propose a model to explain these differences in the morphology of phreatovolcanic constructs between Mars and Earth. Typical terrestrial rootless cones form atop a stable stationary lava crust (e.g., Fagents and Thordarson, 2007) because the lava flows were emplaced relatively slowly. But the Athabasca Valles lava was emplaced as a turbulent flood, so these PCs formed atop a relatively thin and moving crust (Jaeger et al., this issue). The result is that the crust sags under the load of the cone, producing the observed moats. When the crust is carried past the source of steam (which is fixed to the substrate), chains of cones form. When the explosions are spaced closely enough to disrupt the deposits from the earlier explosion, the chain of cones transitions to a continuous wake. The unusual features found associated with the Athabasca PCs are simply the result of their forming on a type of lava flow that is very rare on Earth – a broad sheet flow with a thin crust translating atop the fluid interior (Jaeger et al., 2007). This model also explains the observed correlation between the location of PCs and the substrate topography. The buried terraces and scarps allow ground water to be more readily brought into contact with liquid lava. Cones will preferentially form over buried topographic highs because the overburden pressure is the lowest and because steam may buoyantly accumulate in these locations. Groundwater flow to buried scarps allows locally enhanced steam

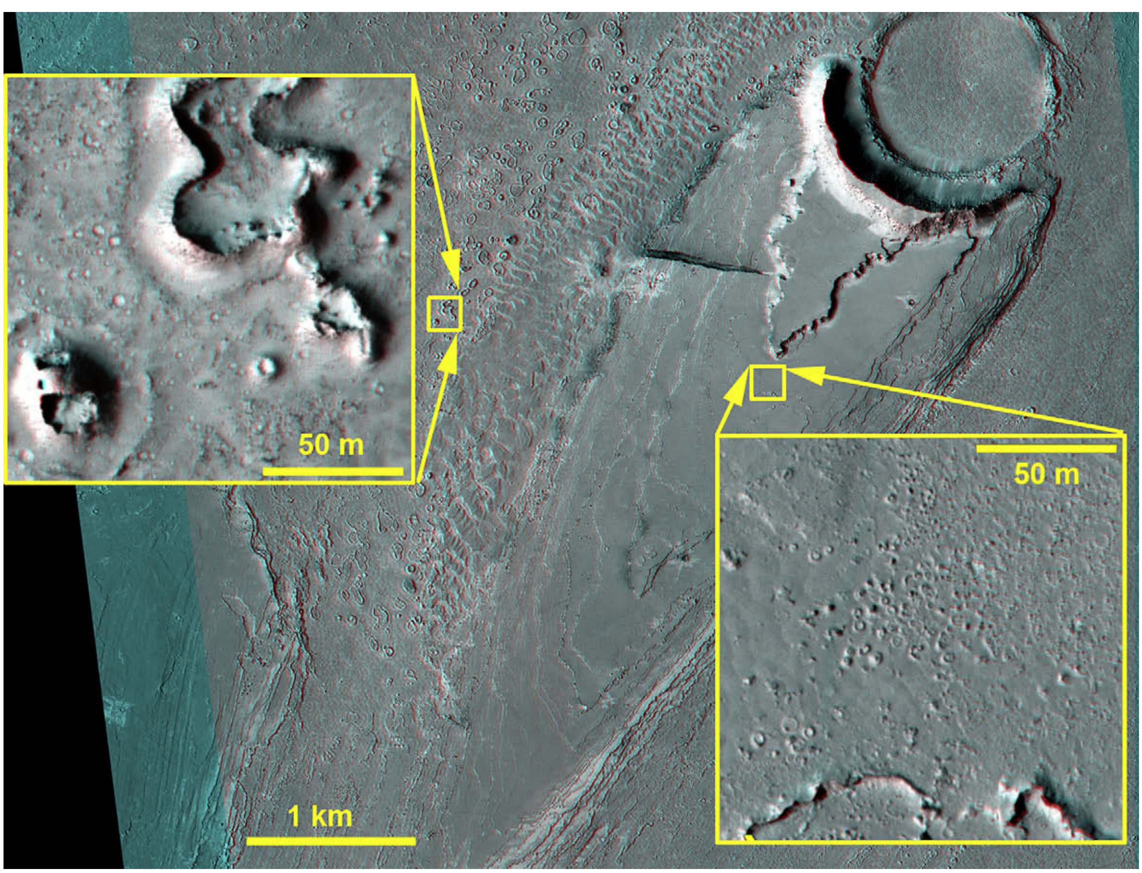

Fig. 1. Rootless cones in the medial section of Athabasca Valles. The electronic (online) version of the figure is a red–cyan anaglyph constructed from HiRISE observations PSP_002661_1895 and PSP_003294_1895 at a scale of 29 cm/pixel. Figure centered at 9.48°N, 156.34°E. The large streamlined hill in the center of the figure is an erosional feature left in the lee of the >1.5 km diameter impact crater. Lava coats the entire scene except for the highest crescent of the eroded crater rim. Rootless cones are found at all elevations on this lava carapace. However, at the uppermost levels, the cones are predominantly just a few meters in diameter (lower inset), as opposed to tens of meters across on the valley floor (upper inset). North is up in this and all subsequent figures. Also, illumination is consistently from the west (left) in the HiRISE images shown. Finally, note that none of the anaglyphs or other figures are reproduced in color in the printed version of this manuscript. Please refer to the electronic version to see the 3-D and color information.

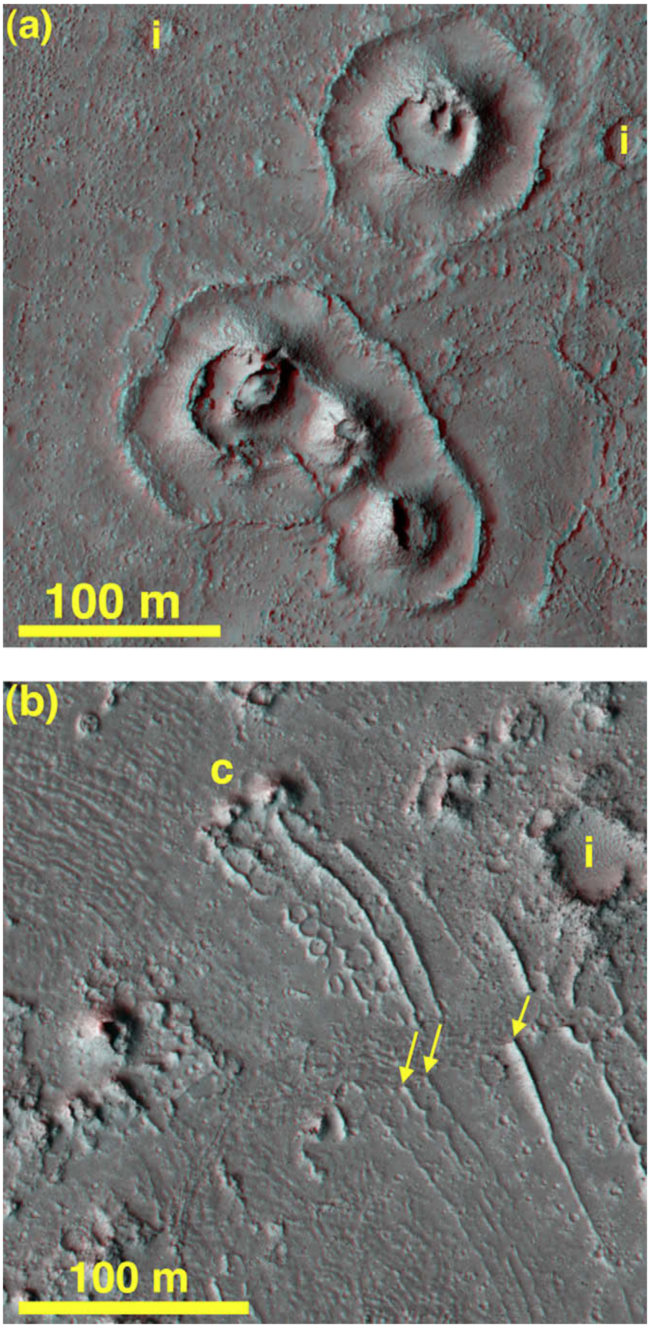

Fig. 2. Wakes and moats associated with rootless cones in Athabasca Valles. (a) Moats surrounding cones in the upper part of Athabasca Valles. Anaglyph constructed from HiRISE observations PSP_001606_1900 and PSP_002226_1900 at a scale of 29 cm/pixel and centered at 9.562°N, 156.436°E. The raised exterior rims of the moats are formed by buckled plates of lava crust that have been thrust out from under the cones. This indicates that they formed in response to the weight of the cone built upon a thin solid crust (Jaeger et al., 2007). **i** indicate small impact craters, probably secondaries from Zunil (McEwen et al., 2005; Preblich et al., 2007) that formed well after the lava flow was emplaced and the rootless cones had formed. (b) Wakes trailing downflow from rootless cones in the distal portion of Athabasca Valles. Anaglyph constructed from HiRISE observations PSP_002648_1880 and PSP_003571_1880 at a scale of 28 cm/pixel and centered at 7.879°N, 153.897°E. c marks a set of three cones that show a continuum between discrete rings and a continuous wake trailing behind them. It is inferred that the western cones had relatively infrequent explosions, producing a series of isolated spatter deposits as the crust translated over the source of the steam. The easternmost cone of this group had relatively vigorous and sustained explosions, producing "levees" of spatter. The fact that the easternmost cone grew the largest after the crust ceases to translate supports this idea. After the formation of the wakes, the crust rafted apart as indicated by the arrows. After flow emplacement, the crater (i) formed, showering the area with boulders.

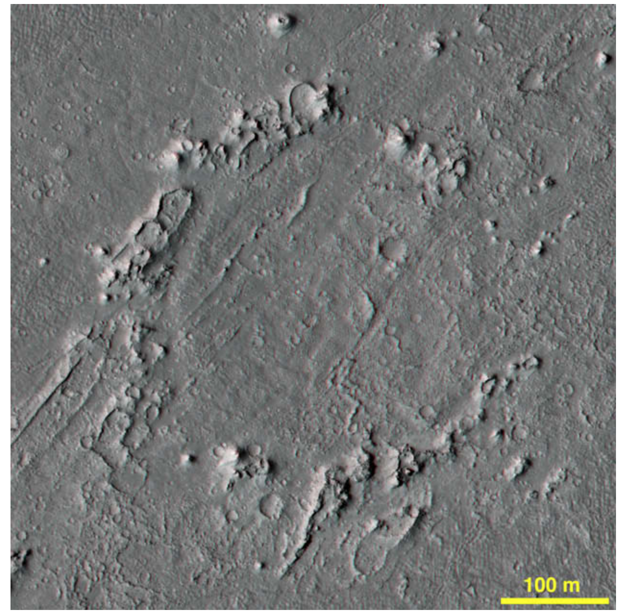

Fig. 3. Rootless cones forming over the rim of a buried impact crater in Cerberus Palus near the terminus of Athabasca Valles. Anaglyph constructed from HiRISE observations PSP_002147_1875 and PSP_002292_1875 at a scale of 28 cm/pixel and centered at 7.434°N, 152.784°E. Jaeger et al. (2007) present the hypothesis that rootless cones will preferentially form over highs in the underlying topography (where the overburden is the least and steam will accumulate).

generation. Cross-cutting relationships and kinematic indicators show that many of the larger explosions took place during the deflation of the lava flow and subsequent lowering of the overburden pressure on the steam (Jaeger et al., 2007).

2.2. Other localities on the Athabasca Valles flow

The lava flow that passed through Athabasca Valles overflowed Cerberus Palus and covered much of western and central Elysium Planitia (Jaeger et al., this issue). The southern edge of Elysium Planitia is marked by a major scarp that is the boundary between the younger plains to the north and the ancient highlands to the south. This section of the boundary is covered by a thick deposit of friable material called the Medusae Fossae Formation (MFF) (e.g., Bradley et al., 2002). One of the defining characteristics of the MFF is the wind erosion that carves it into spectacular yardangs (e.g., Ward, 1979; Bradley et al., 2002; Bridges et al., 2007). While the origin of the MFF is still debated, it is generally thought to be a series of pyroclastic deposits (Bradley et al., 2002) associated with eruptions of either the Tharsis volcanoes (Scott and Tanaka, 1982; Edgett et al., 1997; Hynek et al., 2003) or the flood lavas in Elysium Planitia (Keszthelyi et al., 2000).

The Athabasca Valles flood lavas have draped the smaller yardangs along the southern margin of the Cerberus Palus basin (Fig. 4). Cones indistinguishable from the PCs in Athabasca Valles are found along this margin (Lanz and Saric, 2009). The cones are found concentrated atop the buried yardangs (e.g., Fig. 4b). These concentrations atop buried topographic highs match the conceptual model developed for Athabasca Valles (Jaeger et al., 2007). While the similarity to the cones in Athabasca Valles is very clear, many of the cones near the MFF appear to be partially filled with a light-toned, presumably eolian, material. The most likely source of these eolian materials is the eroding MFF, but gradual accumulation of deposits from dust storms is also plausible.

An interesting observation in this area is that many of the cones are surrounded by a light-toned apron that preferentially exhibits many small craters (Fig. 4c). A deposit of unwelded spatter or sco-

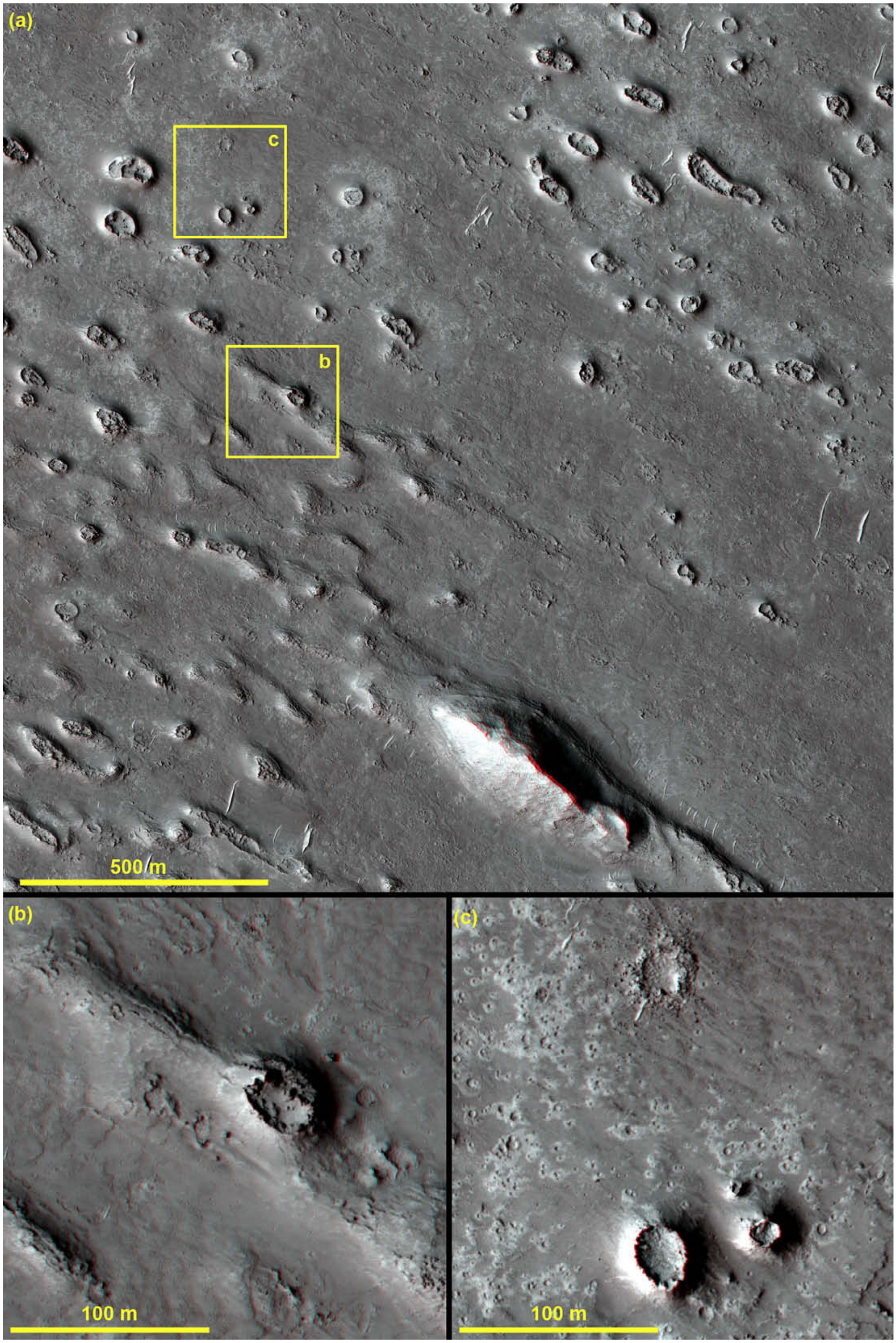

Fig. 4. Rootless cones along the southern margin of Cerberus Palus. (a) Portion of HiRISE anaglyph constructed from observations PSP_002622_1820 and PSP_002411_1820 centered at 1.99°N, 144.86°E. The lava flow in this location has embayed the wind eroded Medusae Fossae Formation (MFF), entirely draping the smaller yardangs. The lava only reaches up a short way on the tallest outlier of the MFF seen in the southern part of this figure. The phreatovolcanic activity was concentrated along the tops of the buried ridges, as seen in the elongated cones in the southwestern part of the figure. (b) Close up of a phreatovolcanic construct (PC) atop a buried yardang. Note the fractures in the lava crust as it failed in a brittle fashion during the deflation of the lava flow. (c) Close up of cluster of small craters with light toned ejecta. These curious craters are only found in the aprons surrounding PCs, suggesting a genetic relationship. We suggest that very small impacts into unconsolidated spatter might produce such craters. The same impacts into the hard lava would not produce craters (see the larger impact crater in the northern part of the figure). The light tone of the ejecta may be dust trapped in the impact ejecta. Alternatively, it could be remnants of a mantling deposit that was indurated by the impact ejecta.

ria surrounding the cone may be able to explain this curiosity. It is plausible that there are many very small impactors that do not produce craters resolvable by HiRISE on the hard lava but these same impacts produce meter scale craters in the pyroclastic deposit. The spatter and scoria would be coarse enough to resist eolian erosion, preserving the small impact craters. Alternatively, these craters may have been produced by bombs ejected during the phreatovolcanic explosions. The light tone of the apron could be a primary characteristic of the pyroclasts or, more likely, the small-scale roughness of the deposit enhances the retention of light-toned dust.

Other nearby observations support the idea that the impact crater-size-distribution, at small diameters, is strongly influenced by the substrate's strength. While the origin of the smallest (<10 m diameter) craters is uncertain, nearly all of the >10 m diameter craters on the surface of the Athabasca Valles lava flow formed as a result of a single event. When an asteroid (or comet) hit Mars and formed the 10-km diameter Zunil Crater, the explosion flung >10^7 large rocks across the surface of Mars (McEwen et al., 2005). The impact craters seen on the Athabasca Valles lava flow were produced when these rocks hit the lava surface, producing "secondary" craters larger than 10 m in diameter. Murray et al. (2005, 2007) have collected impact crater-size-distributions from various parts of the lava flow in Cerberus Palus. They find that the surfaces of rafted plates have systematically larger craters than the smooth polygonally fractured surfaces between the plates. The plates are composed of brecciated lava, while the polygonal interplate surfaces are coherent lava similar to that found on a lava lake (Keszthelyi et al., 2004). Tests in Hawaii have shown that an explosion will form a larger cavity in a brecciated flow top than in a coherent pahoehoe surface (Lockwood and Torgerson, 1980).

Small, relatively isolated cones can also be found along the northern and western margins of the Cerberus Palus basin. Fig. 5 shows some of these features. PCs are notably absent from the images to date covering the central part of Cerberus Palus. This suggests that the local conditions in the main basin were not favorable for the formation of phreatovolcanic explosions. While it is possible that the ground here was less wet than in either Athabasca Valles or the topographically lower channel to the south, the lack of PCs may just indicate that the lava flows in the central part of the basin were too thick for steam to explode though. Murray et al. (2005) estimate that the flows here were ~45 m thick, while the lavas draping Athabasca Valles ended up only some meters thick (Jaeger et al., 2007).

An additional interesting feature seen in Fig. 5 is the small wrinkle ridge that cuts across the very young lava flow. Since the margin of the lava flow is not at a consistent elevation, and instead appears to be deformed by the wrinkle ridges, Jaeger et al. (this issue) conclude that some tectonic activity took place after the lava flow was emplaced. We speculate that the most recent deformation was the result of the loading of Cerberus Palus with lava.

At the southern edge of Cerberus Palus, the lava flow continued to the west, through a broad channel along the northeastern margin of Aeolis Planum, and into the far western parts of Elysium Planitia (e.g., Tanaka et al., 2005). These parts of the flow were only sparsely sampled by HiRISE, but fields of cones are found in

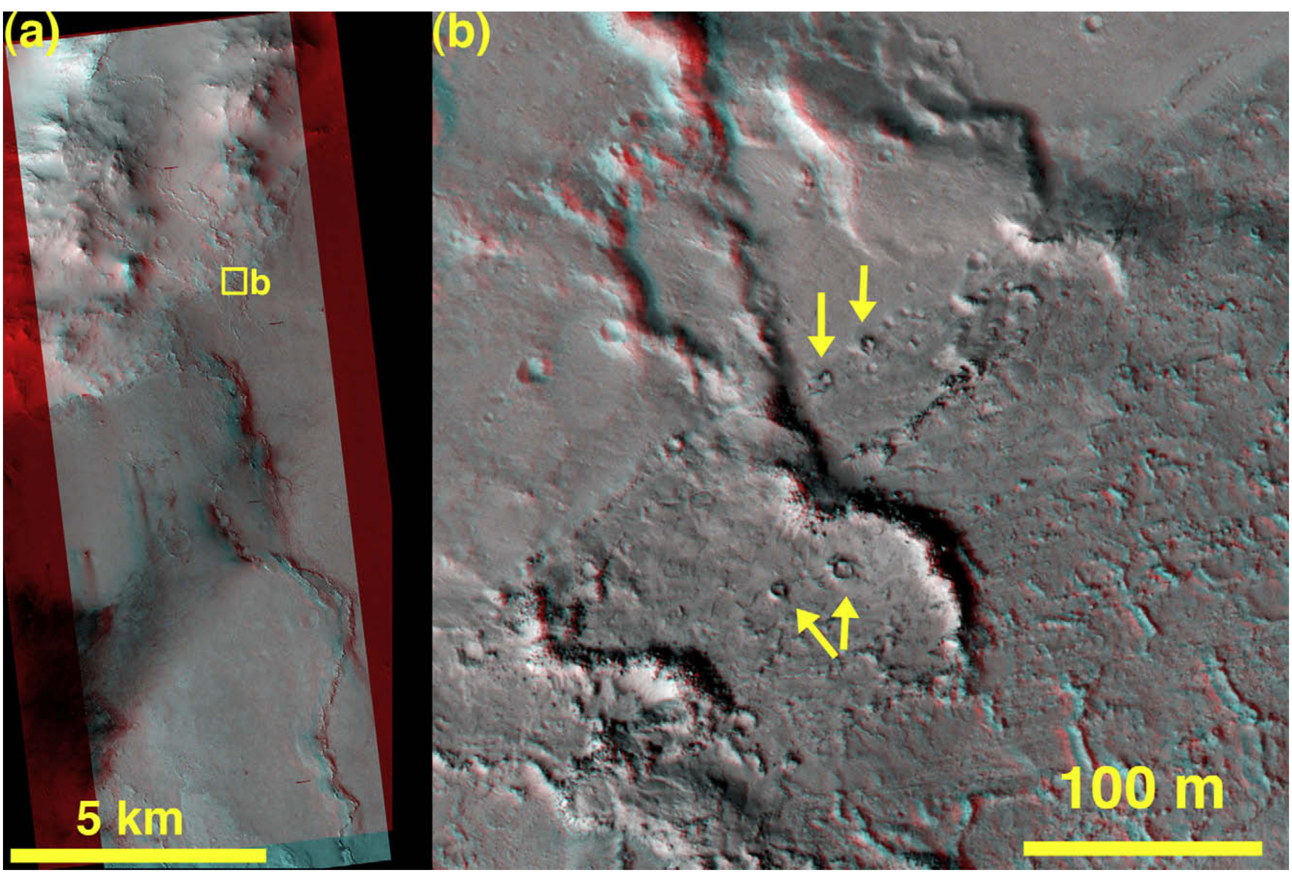

Fig. 5. Isolated rootless cones along the western margin of Cerberus Palus. (a) Thumbnail of anaglyph produced from HiRISE images PSP_003914_1890 and PSP_004191_1890 centered at 9.11°N, 150.50°E. The lighter-toned hills in the northwest are knobs of older terrain. The margin of the lava flow is marked by a distinct darkening of the surface, perhaps due to greater roughness. The diffuse dark patches are formed by removal of dust by the wind. Yellow box shows the location of the inset. (b) Inset of the margin of the lava flow. Arrows point to isolated rootless cones. Other small circular features are impact craters. The few and relatively small cones in this location indicate that the conditions were not a favorable for hydrovolcanic explosions as in the other locations discussed. Also, the small wrinkle ridges that cut across the flow margin indicate that compressional deformation took place after lava flow emplacement. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

multiple locations. The lava flow also exits Cerberus Palus to the east through Lethe Vallis and cones are found on the lava that drapes this smaller flood-carved channel system. As in Athabasca Valles, the PCs are concentrated along the margins of the lava flow. However, the moats and wakes are largely absent, presumably because the lava crust was stable at the time of the explosions in these distal parts of the lava flow.

2.3. Other channel systems in Elysium Planitia

Athabasca Valles is not the only valley system in Elysium Planitia. To the north is Grjotá Valles, to the east is Rahway Valles, and Marte Vallis connects Elysium Planitia to Amazonis Planitia (Burr et al., 2002; Plescia, 2003). These channel systems are geologically very young but significantly older than Athabasca Valles (Burr et al., 2002). To date, probable rootless cones have only been found associated with Grjotá Valles. However, HiRISE imaging of these areas is significantly less complete than Athabasca Valles. While small groups of rootless cones have been found in eight images, the overall distribution of these features in the channel system is not yet known. What is known is that Grjotá Valles bears many similarities to Athabasca Valles. It starts from a segment of the Cerberus Fossae and is surrounded by lava-draped flood-carved landforms. The lava exhibits the same polygonal and platy-ridged textures as seen in Athabasca Valles. However, neither the water nor the lava was as tightly constrained by pre-existing topography, allowing the flow to be distributed across a broad area. This makes it significantly more difficult to trace the extent of the Grjotá Valles flood(s) and lava flow(s). While further investigation may discover evidence for phreatovolcanism in Rahway and Marte Valles, the preliminary suggestion is that the temporal and spatial relationship between floods of water and lava were not always the same as seen at Athabasca Valles. As described in Section 3.1 and in Milazzo et al. (2009), in the case of Marte Vallis, water may have flowed onto a still cooling lava flow. We have seen no evidence that liquid water and hot lava interacted in Rahway Valles.

2.4. Other possible phreatovolcanic constructs

The largest concentration of PCs with associated moats and wakes outside of Athabasca Valles is along the southern margin of Arcadia Planitia. In this location, the northern plains grade into the hilly and knobby terrain of the Phlegra Dorsa, Phlegra Montes, and Tartarus Montes. Northward of about 40°N, the plains are extensively reworked by periglacial processes and the nature of the original surface is widely debated (e.g., Tanaka et al., 2003, 2005; McEwen et al., 2007b). However, below ~30°N, degraded volcanic surface features can be identified. Abundant PCs, some forming spectacular chains and wakes (Fig. 6), as well as dense "cone fields" (Fig. 7) are found in the region approximately bounded by 25–28°N, 165–190°E. This area is mapped as Middle to Lower Amazonian in age (Tanaka et al., 2005), corresponding to sometime between 0.3 and 3.4 Ga (Hartmann and Neukum, 2001). The cones are generally well-preserved, but some infilling and degradation by mass wasting is evident.

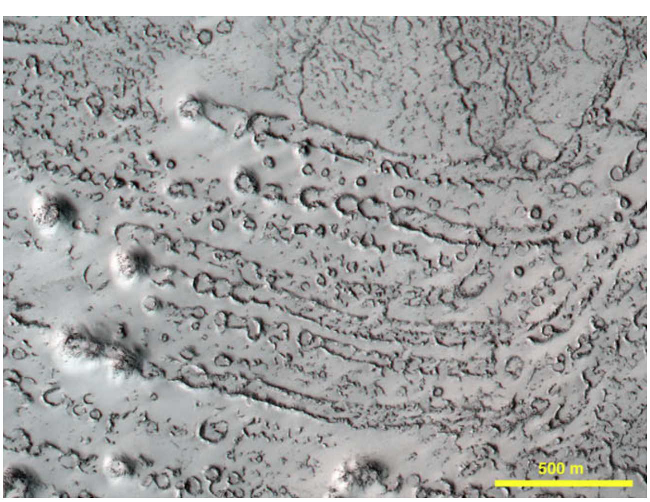

Fig. 6. Chains of rootless cones near the southern margin of Arcadia Planitia in the Tartarus Colles. Anaglyph produced from HiRISE images PSP_006748_2060 and PSP_006959_2060. Figure is a reduced resolution subsection centered at 25.988°N, 173.729°E. As in Athabasca Valles, the chains are interpreted to have been produced by successive explosions as the crust was translating over a fixed steam source. Where the explosions overlapped, the cones merge into parallel wakes.

In many areas, the surface around the cones exhibits well-preserved platy-ridged morphologies (e.g., the northern portion of Fig. 7a). This greatly enhances our confidence in interpreting these mounds and cones as phreatovolcanic in origin. However, other areas have an enigmatic warped and pitted texture (e.g., Fig. 7c). The 200-m scale pits appear to be largely devoid of competent rock. They are not associated with cones or mounds or other evidence for a constructional origin. Instead, they appear to be collapse features caused by the loss of volume in a largely unconsolidated layer, somewhat similar to the "ponded and pitted" terrain HiRISE discovered in many young impact craters (McEwen et al., 2007b). That impact-generated texture is suggested to be indicative of collapse due to the loss of volatiles in the fallback ejecta, and an analogous process may be at work here. Interestingly, the margin of this pitted terrain is marked by arcuate fractures suggestive of uplift of the surface (Fig. 7a). Overall, the assemblage of surface features is reminiscent of the "enigmatic" uplifts in southern Elysium Planitia described in Fig. 15 of Keszthelyi et al. (2008). The suggested explanation for those features, lava intruding underneath ice-rich sediments and the subsequent sublimation of the ice, could explain the features seen here in southern Arcadia Planitia. The differences might be the result of higher ice content at these higher latitudes.

The only other locality where we have confidently identified a cluster of PCs and associated features is in southern Amazonis Planitia, between Eumenides and Gordii Dorsa. These cones are found in Lower Amazonian – Upper Hesperian terrain where floods of both water and lava debouched from Mangala Valles to the south. They do not appear related to the more recent flows from Elysium Planitia that passed through Marte Vallis into the westernmost part of Amazonis Planitia (Tanaka et al., 2005). The region with the PCs is largely being exhumed from under the Medusae Fossae Formation (MFF) and many isolated knobs and mesas can be found in the HiRISE images.

Fig. 8 shows examples of PCs with moats and wakes. While extensively infilled by MFF material, there are a number of morphologic features that lead us to conclude that these are PCs. The lava surface being exhumed from under the MFF shows rafted plates with ridged surfaces characteristic of martian flood lavas. The cones are found in both isolated clusters (Fig. 8b) and large fields (surrounding Fig 8c). Cones often sit within small topographic depressions (i.e., moats) (Fig. 8b). Chains of cones that transition toward the kinds of wakes seen in Athabasca Valles are also present (Fig. 8c).

What is most surprising is that platy-ridged lava and PCs are apparent on the top of the large mesa along the eastern side of Fig. 8. To further complicate matters, the plates and ridges on the lower plains appear to continue on either side of the mesa. Shadow measurements show that the knobs of MFF in the area are up to 35 m tall. The large mesa appears slightly taller, but appropriate shadows do not exist for height measurements. Stereo imaging has been completed over this location, but elevations have not

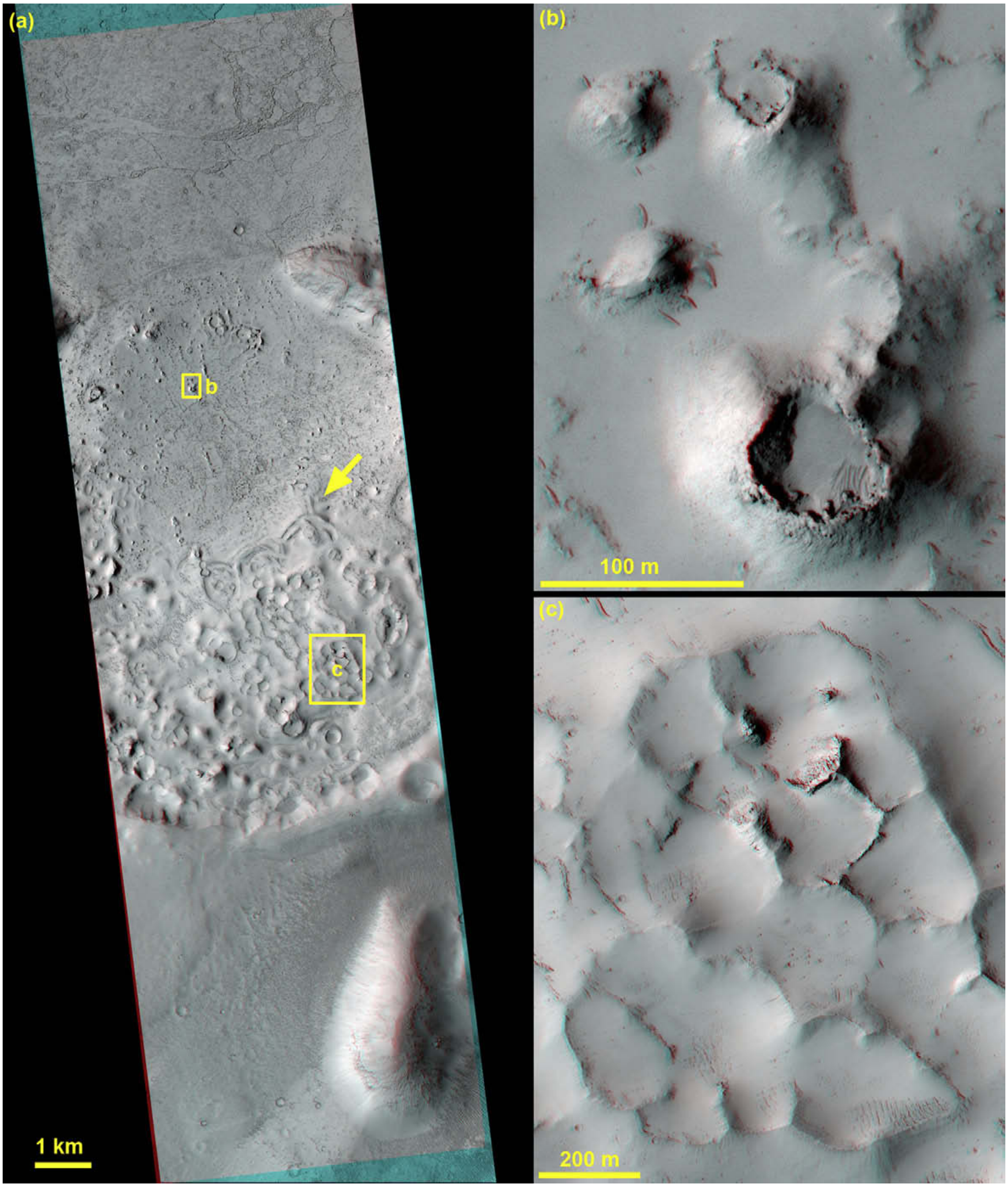

Fig. 7. Cratered cones and pits in southern Arcadia Planitia. (a) Anaglyph constructed from HiRISE observations PSP_007605_2055 and PSP_007961_2055 centered at 25.39°N, 173.51°E. (b) Full-resolution close-up of phreatovolcanic constructs. (c) Close-up of enigmatic pitted terrain. Arrow in (a) points to arcuate fractures discussed in the text.

yet been calculated. The global MOLA elevation map shows that this mesa is on the edge of a much more extensive plateau. We suggest the following sequence of events to explain these observations. First, the flood lavas that make up the lower plains were emplaced. Then MFF materials were emplaced atop the lava flow. Erosion began and the region that is now a plateau became a low area within the MFF. A second flood lava filled the depression, armoring the underlying remnants of the MFF. As erosion continued, the surrounding sections of the MFF were removed, exposing the older flood lavas. If correct, this indicates that the emplacement of the MFF and flood lavas were interleaved. This is at least consistent with the idea that the MFF is largely composed of pyroclastics from the large fissure eruptions that fed the flood lavas (Keszthelyi et al., 2000).

A more tentative interpretation is made of a well-preserved set of cratered cones found in the northern part of the Olympus Mons aureole. The aureole is a broad fan-shaped deposit that surrounds the northwestern sector of Olympus Mons, and while many ideas for its origin have been proposed, it is generally thought to be a giant landslide deposit (e.g., McGovern et al., 2004). Large volcanoes undergo gravitational collapse as they grow on Earth (e.g., Van Wyk de Vries and Francis, 1997) and modeling suggests this should take place on Mars as well (McGovern et al., 2004). Along its western margin, the aureole is embayed by the same flood lavas

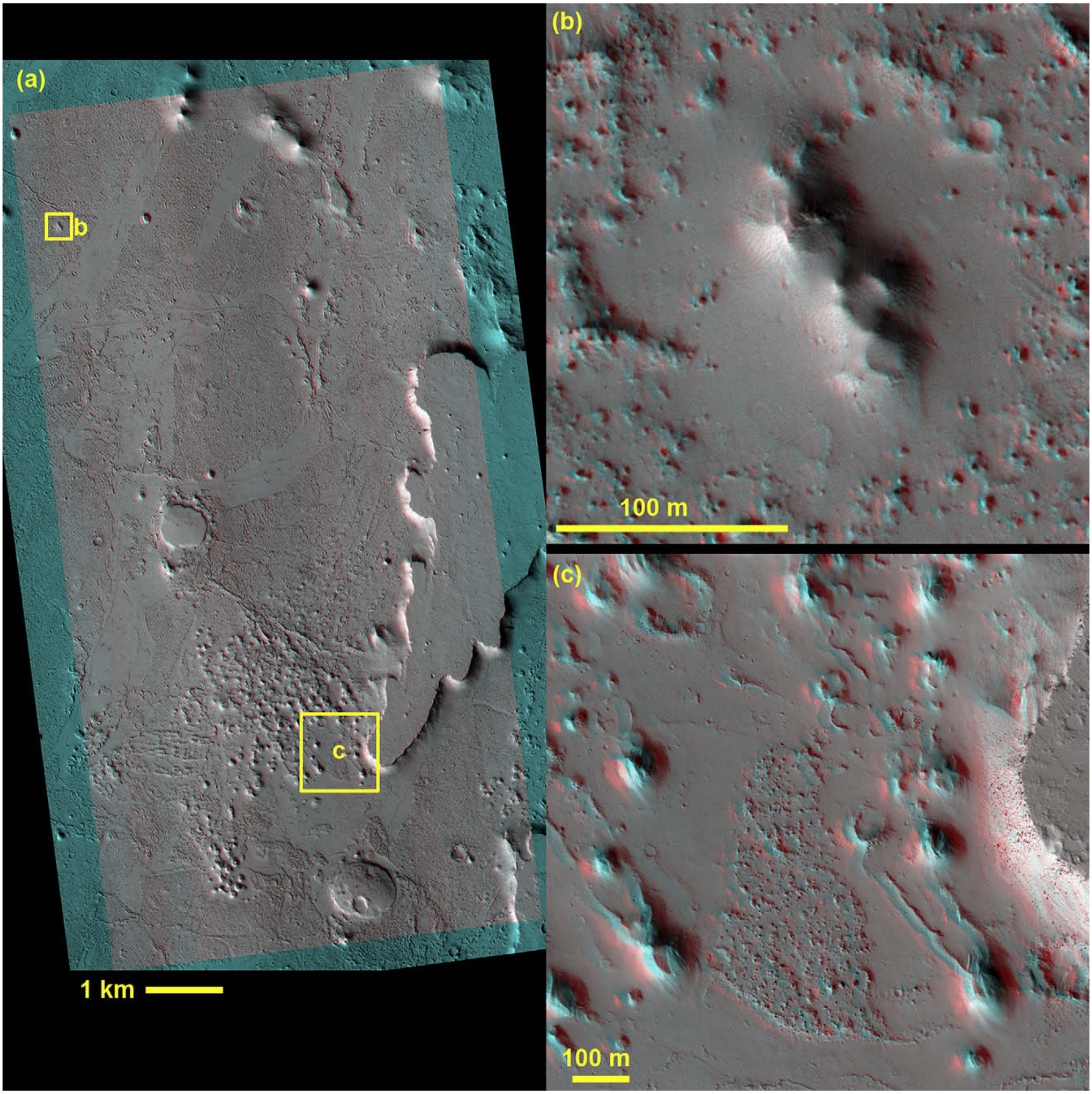

Fig. 8. Rootless cones in Amazonis Planitia. (a) Thumbnail of anaglyph produced from HiRISE observations PSP_003701_1915 and PSP_004202_1915 centered at 11.52°N, 204.99°E. The circular and irregular plateaus, as well as the isolated knobs are remnants of the Medusae Fossae Formation capped by lava. (b) Close-up of an isolated group of cones sitting within a moat. (c) Close-up of a chain of cones transitioning into a wake.

that fill Amazonis Planitia while the northern portion appears to have been embayed by broad lava flows possibly flowing from the southwest off of the Tharsis bulge.

These cones have the same general morphologies as the PCs in Athabasca Valles, ranging from mounds to cratered cones to ameboid ring structures (Fig. 9). The rims of the cones are composed of competent rock that sheds boulders. While they do not form clear chains, wakes, or moats, the general distribution is qualitatively similar to the more randomly distributed PCs in and around Elysium Planitia. However, these cones are distinctly larger than the more definitive examples of PCs. In this cone field, the diameters are generally >100 m, with a mode around 300 m. We also cannot confirm that these features are situated on top of a lava flow because the region is extensively mantled. The style of degradation of this mantle suggests that it is ice-rich. If a lava flow were to have been emplaced over such a mantle, explosive interactions may be expected. Overall, a hydrovolcanic origin for these cones is quite plausible, but not conclusively supported by the HiRISE data.

Cratered cones seen in three images (PSP_002095_2130, PSP_006658_2135, and PSP_008464_2140) in Utopia Planitia near 33°N north are more dubious PCs. These features have a size range similar to the Athabasca Valles PCs. They also may be on a volcanic surface and there are hints of moats around some cones. However, the features are also substantially degraded by impacts, dust infilling, and periglacial processes. The surface may also be composed of mudflows, rather than lava flows (see Section 3.2). We conclude that the evidence that these features are phreatovolcanic in origin is equivocal.

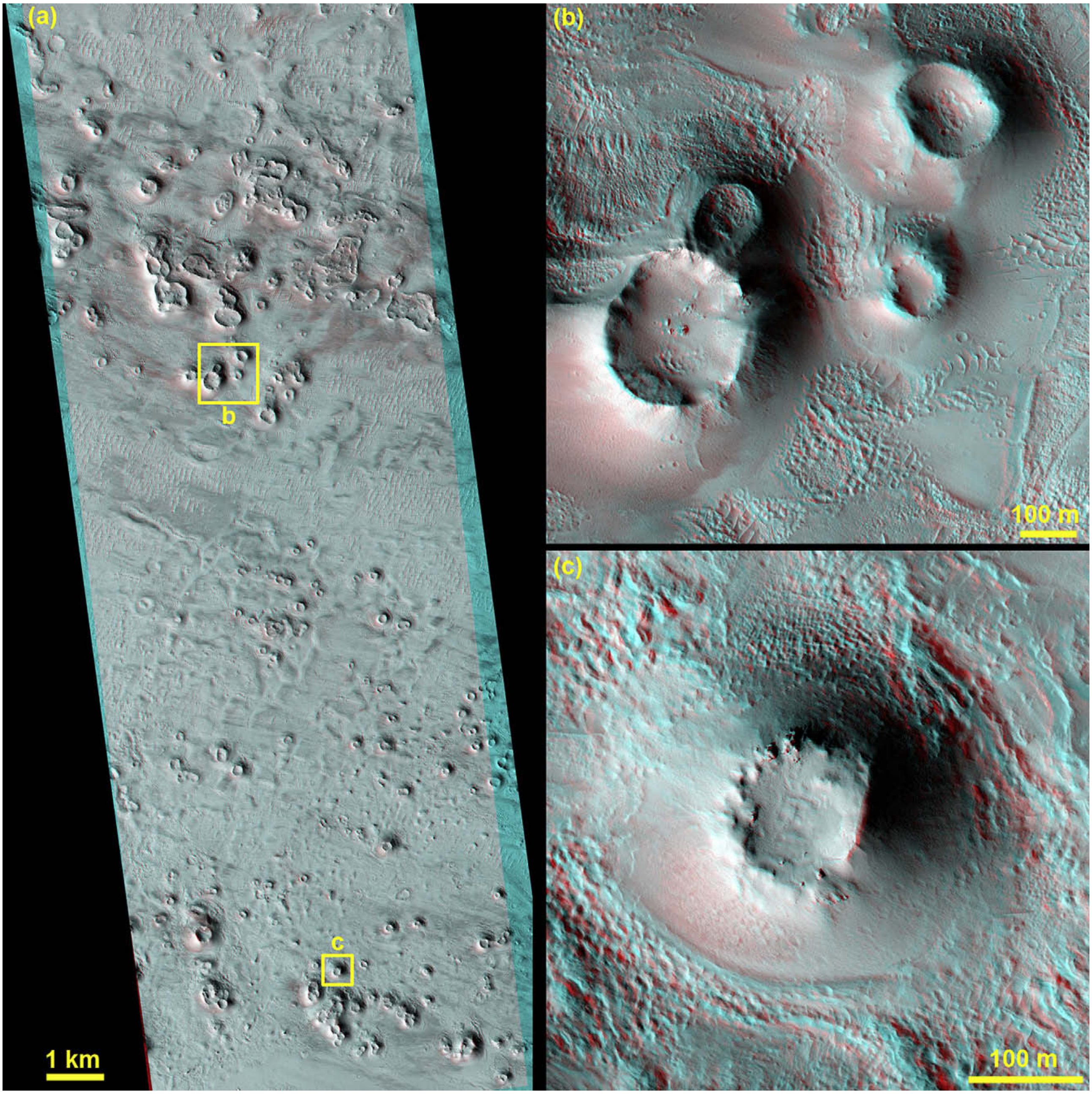

Fig. 9. Cratered cones north of Olympus Mons. Anaglyph constructed from HiRISE observations PSP_006667_2150 and PSP_006957_2150 centered at 34.45°N, 225.12°E. (a) Overview of the cone field, showing the range of sizes and morphologies as well as their spatial distribution. (b) Close-up of larger northern cones. (c) Close-up of smaller southern cones (note the scale bars). These cones are substantially larger than those found in Athabasca Valles but exhibit exposures of hard rock and boulders. Also note the thick mantling deposit that appears to preferentially accumulate on the pole-facing slopes. This mantle is undergoing degradation by mass wasting and the loss of volume, presumably via the sublimation of volatiles.

2.5. Other cratered cones unlikely to be of hydrovolcanic origin

There are a variety of cratered cones seen on other parts of Mars for which we find the evidence for a hydrovolcanic origin to be unconvincing but plausible enough to merit some discussion. In the cases described below, evidence for the interaction of hot lava and liquid water is weak, but alternative hypotheses are also lack definitive observational support.

A locality with cratered cones of similar scale as seen in Athabasca Valles is Kamativi Crater, located at 20.5°S, 100.1°E, which is east of Tyrrhena Patera. Tyrrhena Patera is the broad summit depression within a ~1000 km by 200 km shallow volcanic edifice (Greeley and Crown, 1990; Gregg and Farley, 2006). The flanks of this edifice are thought to be constructed of a mix of lavas and pyroclastic deposits formed in the Late Noachian to Early Hesperian (~3.5 Ga), though some resurfacing may have continued into the Amazonian at 1.1–1.6 Ga (Gregg et al., 1998; Hartmann and Neukum, 2001; Williams et al., 2006). PSP_008979_1595 shows a dense cluster of 20–50-m scale cratered cones, mounds, and raised rings near the center of this ~40 km diameter impact crater (Fig. 10). The size and general morphology of these features is broadly similar to the PCs in Athabasca Valles. Given the close proximity of this crater to a major volcanic center, it is plausible that lava flows from Tyrrhena Patera would have entered the

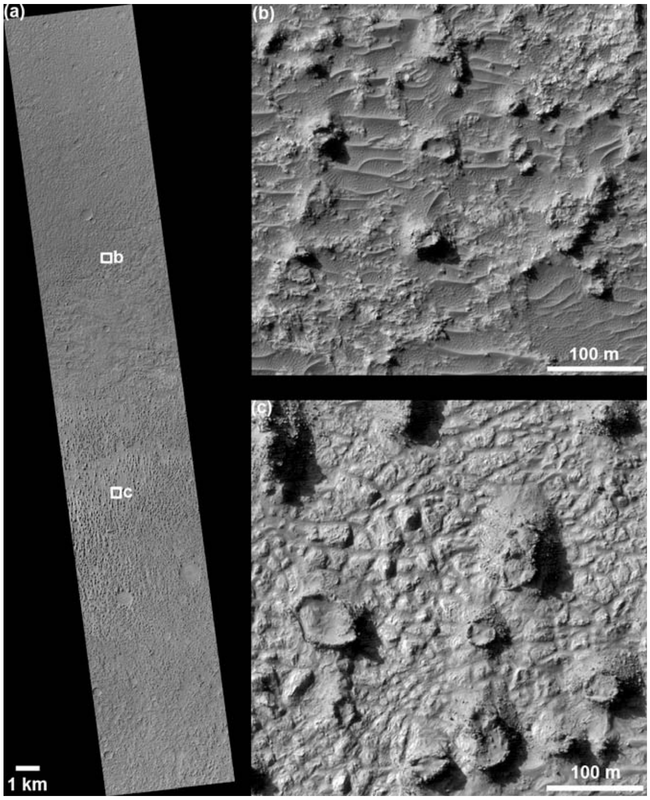

Fig. 10. Enigmatic cones and mounds in Kamativi Crater. (a) Thumbnail of HiRISE image PSP_008979_1595 centered at 20.486°S, 100.088°E showing the location of the two full resolution cutouts. (b) Northern cutout showing cratered cones, mounds, and irregular ridges surrounded by aeolian bedforms and limited bedrock exposures. (c) Southern cutout showing more cratered cones with well defined resistant rims and irregular mounds atop clearly exposed fractured bedrock. While we cannot rule out a hydrovolcanic origin for these cones and mounds, they are more likely to be erosional remnants of a partially indurated mantling deposit.

depression. The walls of the crater are locally modified by channels with a fluvial appearance, so the floor of the crater could have been wet at the time the lavas were emplaced.

There are two major factors arguing against a hydrovolcanic origin for these features. First, the substrate does not exhibit textures similar to lava flows seen on Mars or Earth. Instead, the rectangular patterns are more similar to those found on various clay- or evaporite-rich surfaces (c.f., Wray et al., 2008). Second, the cluster of cones and rings transition gradually to a more continuous pitted surface. This suggests that the discrete cones, mounds, and rings are erosional remnants of this more continuous pitted mantling material. We favor the erosional hypothesis, but are unable to definitively rule out a hydrovolcanic origin for these enigmatic features.

A distinctly different type of cratered cone can be found throughout Isidis Planitia, in many parts of Utopia Planitia, and in other patches of the northern plains near the dichotomy boundary (Fig. 11). These cones are significantly larger than the typical Athabasca Valles PCs (~500 m vs. 40 m modal diameter). Especially in Isidis Planitia, they are aligned in spectacular chains. However, unlike the Athabasca Valles-type chains, the Isidis cones do not overlap or transition into parallel wakes.

Tanaka et al. (2003, 2005) suggest that the area is covered by an extensive sedimentary deposit from the erosion of the dichotomy boundary. As this deposit dewatered, a number of different landforms would be expected to form, including mud volcanoes. Mud volcanism may have been triggered by large seismic events such as impacts or faulting (Komatsu et al., 2007; Skinner et al., 2008). We favor this mud volcano hypothesis because: (a) there is no evidence that the substrate is a lava flow and (b) there is a striking morphologic similarity between the Isidis cones and terrestrial seismically triggered mud volcanoes (c.f., Obermeier, 1998). The chain of cones in Fig. 11 appears to lie along a buried thrust fault, again analogous to the geologic setting of many of the larger terrestrial mud volcanoes (Obermeier, 1994).

Along more northerly sections of the eroded dichotomy boundary, there are additional cratered cones and mounds. These are most prominent in Acidalia Planitia, including the Cydonia region (Fig. 12). While initially suggested to have a hydrovolcanic origin (Frey et al., 1979), these features are now generally thought to involve the dewatering of wet sediments. The range of features could be explained by the variety of processes that can be involved in the compaction of wet sediments, all of which can fall under the broad definition of mud volcanism (Farrand et al., 2005).

HiRISE images show that the surface of many of these mounds and cones grade into the nearly ubiquitous "mid latitude" mantle that is generally interpreted as ice-rich dust (Mustard et al., 2001). At full resolution, the HiRISE data show no evidence of competent rock, and only very few boulders, in these features. This lack of hard rock is striking because the surrounding plains often contain a significant concentration of resolved boulders. This, and the presence of polygonal fractures that are consistent with desiccation or thermal contraction cracks, support the idea that these cones and mounds are composed of fine-grained sediment. Overall, the HiRISE data are consistent with the mudvolcanism hypothesis and provide no evidence to support a hydrovolcanic origin for these features.

2.6. Cratered cones formed by non-volcanic processes

It is important to briefly mention that there are cratered cones on Mars that were previously enigmatic but are now clearly seen to have been formed by non-volcanic processes. We show examples of two types of features that have caused some confusion in the past. As previously mentioned, HiRISE has found examples of possible pingos on Mars (Dundas et al., 2008; Dundas and McEwen, 2009). Fig. 13 shows one example of a mound that may be a pingo with an extant ice-core and thus has not collapsed.

Alternatively, it is a remnant landform left by some form of latitude-dependent erosion (Dundas and McEwen, 2009). At lower resolution or after some degradation, such features would be very difficult to distinguish from isolated mound-like hydrovolcanic constructs. However, when well-resolved, pingos can be identified by the set of fractures associated with the uplift. Instead, uncollapsed pingos are more similar to "tumuli" on a lava flow, which are mounds formed by localized injection of lava underneath a solidified lava crust (e.g., Walker, 1991; Hon et al., 1994). The nature of the substrate that is being uplifted (sediment versus lava flow) is sometimes the strongest indicator of the way uplifted mounds may have formed, though pingos also preferentially form in certain topographic settings. Partially collapsed pingos can form cratered cones that are morphologically indistinguishable from rootless cones in orbital images. The geologic and hydraulic setting, as well as the spatial distribution as described in Bruno et al. (2006), are important to consider when deciding between a hydrovolcanic and pingo origin for a cratered cone. As noted earlier, moats and chains of cones grading into wakes are characteristics that are indicative of phreatovolcanism.

Another type of feature that is often confused with phreatovolcanic cones is the pedestal crater (Fig. 14). In fact, a number of the PCs that are filled and mantled with aeolian deposits or the MFF (e.g., Figs. 8–11) have a very similar appearance to pedestal craters. In this case the identification is simple because the cone is atop the MFF and there is no evidence for an underlying lava flow. Furthermore, the erosion on the flanks does not expose any competent rock that could be welded spatter. Finally, the size of this feature

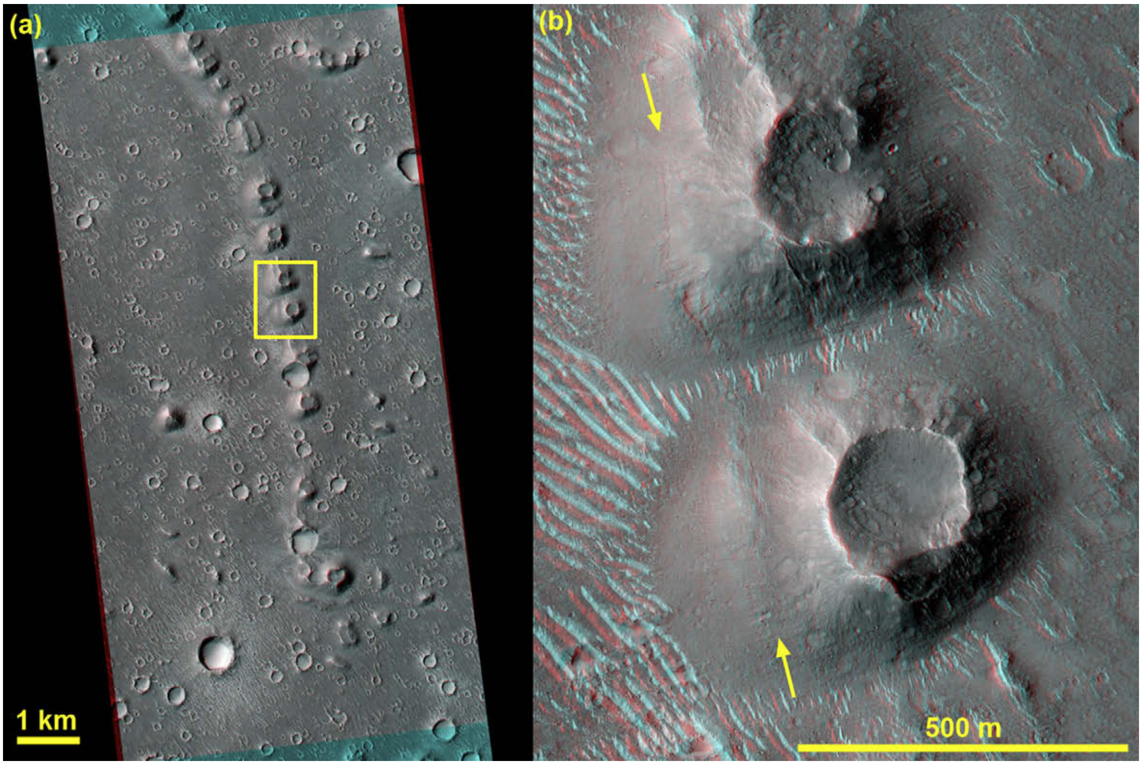

Fig. 11. Chain of cratered cones in Isidis Planitia. Anaglyph constructed from HiRISE observations PSP_008887_1985 and PSP_009177_1985 centered at 18.13°N, 88.23°E. (a) Is an overview of the entire stereo pair, showing the remarkable arrangement of cones in a curving chain. The yellow box shows the location of the inset (b). These cones are approximately an order of magnitude larger than the larger phreatovolcanic cones in Athabasca Valles, do not appear to be composed of competent rock, and the surrounding surface does not show features indicative of a primary lava flow. For these reasons we do not favor a phreatovolcanic origin for these cones. Instead, we favor mud volcanism, possibly localized by tectonic faults and triggered by seismic shaking, as proposed by Skinner et al. (2008). In support of this hypothesis, the topography revealed by HiRISE is suggestive of a buried thrust fault underlying the chain of cones. The ground to the east of the chain is higher than that on the west and the arrows in (b) show fractures and protuberances that parallel the hypothesized fault. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

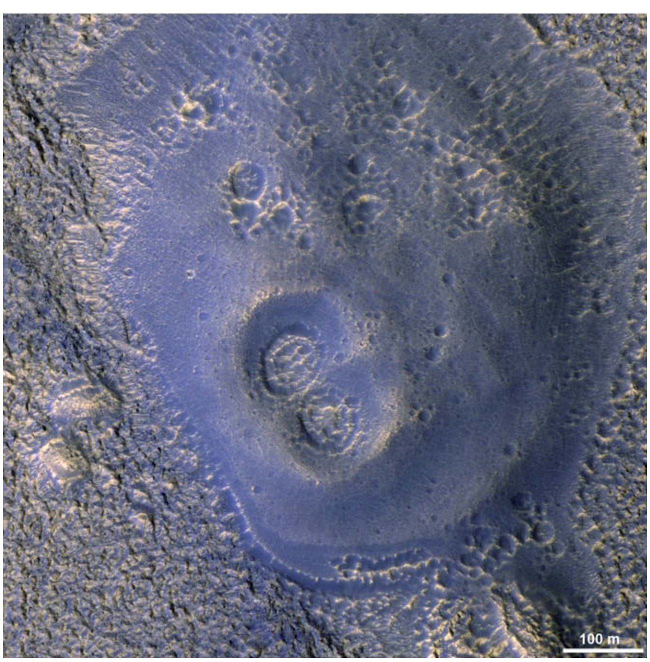

Fig. 12. Dark cratered cone in Acidalia. Portion of HiRISE observation PSP_002232_2180 in enhanced color centered at 37.567°N, 347.267°E. The lack of boulders suggests that this cone is composed of fine-grained material that is not strongly indurated. The surface exhibits polygonal fracturing that could be the result of desiccation. The surrounding plains are composed of degraded mantling material. Overall, the data are most consistent with a mud volcano origin for this feature but the evidence does not rule out other hypotheses.

is atypical of PCs. Thus pedestal craters are the most likely explanation for some large cones in Elysium Planitia.

3. Other hydrovolcanic and hydromagmatic features

3.1. Columnar jointing

The discovery of narrow and fanning columnar jointing on Mars, strikingly similar to entablature on Earth, is reported by Milazzo et al. (2009) and here we only provide a brief summary. The entablature-style columnar jointing was observed in the walls of a 16 km diameter impact crater in Marte Vallis (Fig. 15). The jointing is inherent to the uplifted and tilted lava, and is not a result of the impact process. On Earth, entablature-style columnar jointing in mafic lavas has been empirically correlated with water-cooling (e.g., Raspe, 1776; Mallet, 1875; Iddings, 1886; James, 1920; Tomkeieff, 1940; Long and Wood, 1986). This observation is supported by theory. With simple conductive cooling, the cooling rate decreases rapidly with depth and the density of fractures should also decrease toward the center of a lava flow. To produce the parallel fractures of columnar jointing, an additional cooling mechanism is required. Penetration of water along growing fractures is the most geologically plausible process to provide this additional cooling deep within the flow (e.g., Milazzo et al., 2003; Bahr et al., 2009). Applying previous numerical studies of the cooling of lava flows (i.e., Long and Wood, 1986), Milazzo et al. (2009) estimate that the liquid water was intermittently present for a few months to a few years. This was the best example of entablature found during the Primary Science Phase (Milazzo et al., 2009), but HiRISE has recently imaged another example of similar quality in the wall of a

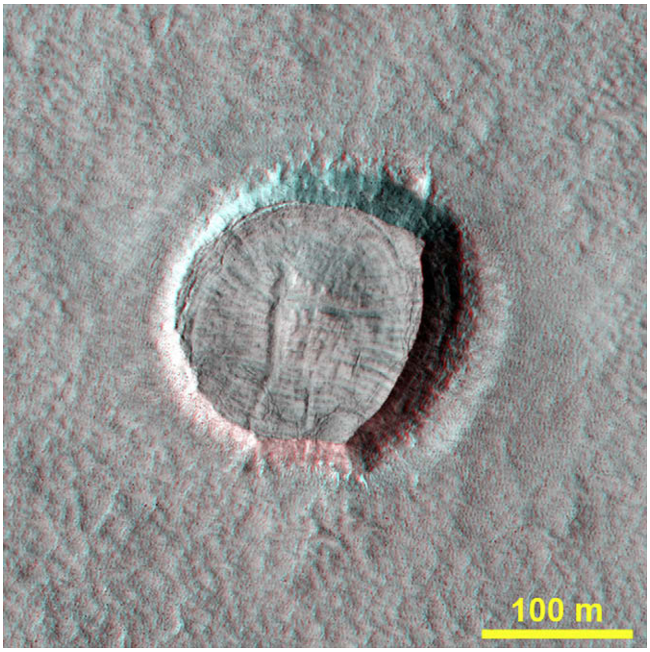

Fig. 13. Possible pingo in southwestern Utopia Planitia. Anaglyph constructed from HiRISE observations PSP_007081_2190 and PSP_009876_2190, centered at 38.592°N, 80.337°E. Note the radial and circumferential fractures indicative of uplift. This fracture pattern is similar to that caused by lava flow inflation, but the overall (flat-topped) shape is uncharacteristic of tumuli. However, individual collapsed and degraded pingos (or pingo scars) may be difficult to distinguish from degraded hydrovolcanic constructs. The spatial distribution and geologic context may help identify the formation mechanism, but the origin of small degraded mounds will often be uncertain. Other (better) candidate pingos on Mars are described in Dundas and McEwen (2009).

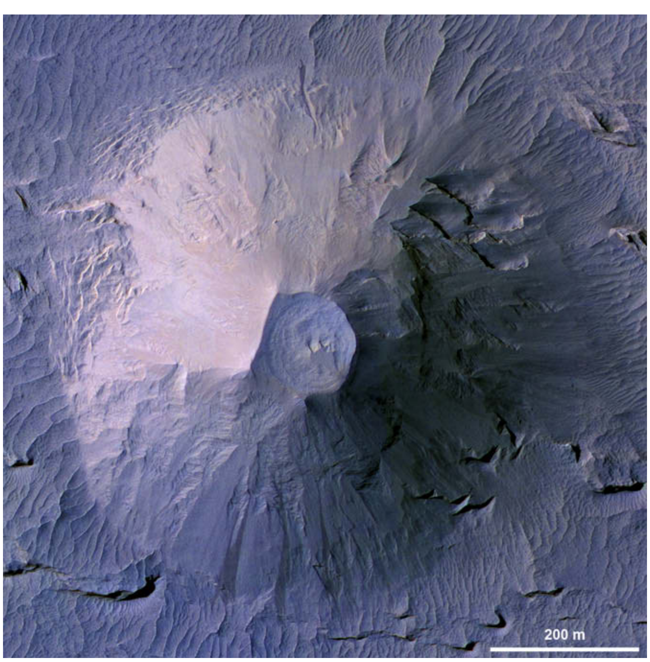

Fig. 14. Cone in the Medusae Fossae Formation. Portion of HiRISE image PSP_007764_1795 in enhanced color centered at 0.297°S, 155.156°E. We interpret this to be a pedestal crater. Impact craters formed in soft materials can indurate a circular area. Subsequent erosion will leave this area elevated and mass wasting produces a flat-topped or cratered cone. Smaller examples can be difficult to distinguish from mantled hydrovolcanic cones, such as seen in Figs. 8–11.

crater in eastern Isidis Planitia (see stereo pair ESP_013238_1945 and ESP_013871_1945).

3.2. Lahars

Lahars are mudflows (debris flows) triggered by volcanic activity. On Earth, they are most commonly associated with hot ash mixing with snow high on a volcano. The mixture of ash and water can descend as a flood of mud with devastating consequences for people living along river valleys downstream. On Mars, the lahars may not require explosive eruptions. Instead, the heat from extrusive flows or even intrusions may be sufficient to trigger widespread melting of ground ice (e.g., Squyres et al., 1987; Head et al., 2003; Head and Wilson, 2007).

The best-documented candidate lahars are found extending from the western and northern flanks of Elysium Mons (e.g., Christiansen, 1989; DeHon et al., 1999; Russell and Head, 2003; Wilson and Mouginis-Mark, 2003). One of the channel systems, Hrad Vallis, has been covered by a significant number of HiRISE images. At the head of the channel system is an elongated embayment with a steep-sided head scarp (southern end of Fig. 16a). On the floor of the depression, the surface exhibits various indicators of flow, including streamlined forms and boulder trains. The bulk of the scarp appears to consist of massive rock (Fig. 16c). However, the upper section shows discontinuous layers of hard rock with a bluer tone. In other localities, such as the walls of Olympus Mons Caldera and the Cerberus Fossae, this color and morphology is associated with mafic lava flows (e.g., Keszthelyi et al., 2008). A layered mantle of boulder-free material overlies the lavas. The scattered boulders all appear to have been shed from the capping lavas. While it is possible that the lower part of the scarp is extensively mantled, these observations suggest that the bulk of the material that is exposed in the scarp is not coherent lava. Instead, a mechanically weak, fine-grained material is suggested.

Outside the source depression (Fig. 16b), the surface is somewhat similar to the pitted terrain in Arcadia Planitia (Fig. 7c). As in the Arcadia example, we infer that a plausible mechanism to form this terrain is the devolatilization of an ice-rich mantle by the intrusion of mafic magma (rather than interaction with lava). Indeed, patches of hard, less red than average Mars, rock that appears to be mafic volcanics crops out in some of the ridges (northern end of Fig. 16b). While none of these features are diagnostic of lahars triggered by intrusions into weak icy rock, they are completely consistent with such a scenario.

The main Hrad Vallis channel is too large to be well characterized by individual HiRISE observations. CTX and THEMIS are better suited for investigating that portion of the flow of viscous materials onto Utopia Planitia. However, a small ($\sim$5 km wide, 30 km long) overflow from the main channel is of a convenient size to illustrate key features of this flow as seen by HiRISE (Fig. 17). While the flow has lobate margins that are clearly indicative of a viscous flow, the surface textures are unlike those reported for lava flows on Earth or Mars. Along the margins, the surface is covered with kilometer-scale corrugations with a wavelength of order 100 m (Fig. 17b). The corrugations are perpendicular to the flow direction, suggesting that they may have formed by compression and folding of a crust. While bearing some similarity to ridges on brecciated lava flow tops, these ridges are far more linear than those typically seen on lava flows. On lavas, the folds are usually arcuate, convex in the downflow direction, due to the higher flow velocity in the center of the flow. The lack of interaction between the trend of the corrugations and the convoluted shape of the flow margin suggests that these ridges formed by some different mechanism, possibly post emplacement.

The buckling and fracturing of the surface of the flow near the center of the lobe is also unlike that of lava (Fig. 17c). The fractures

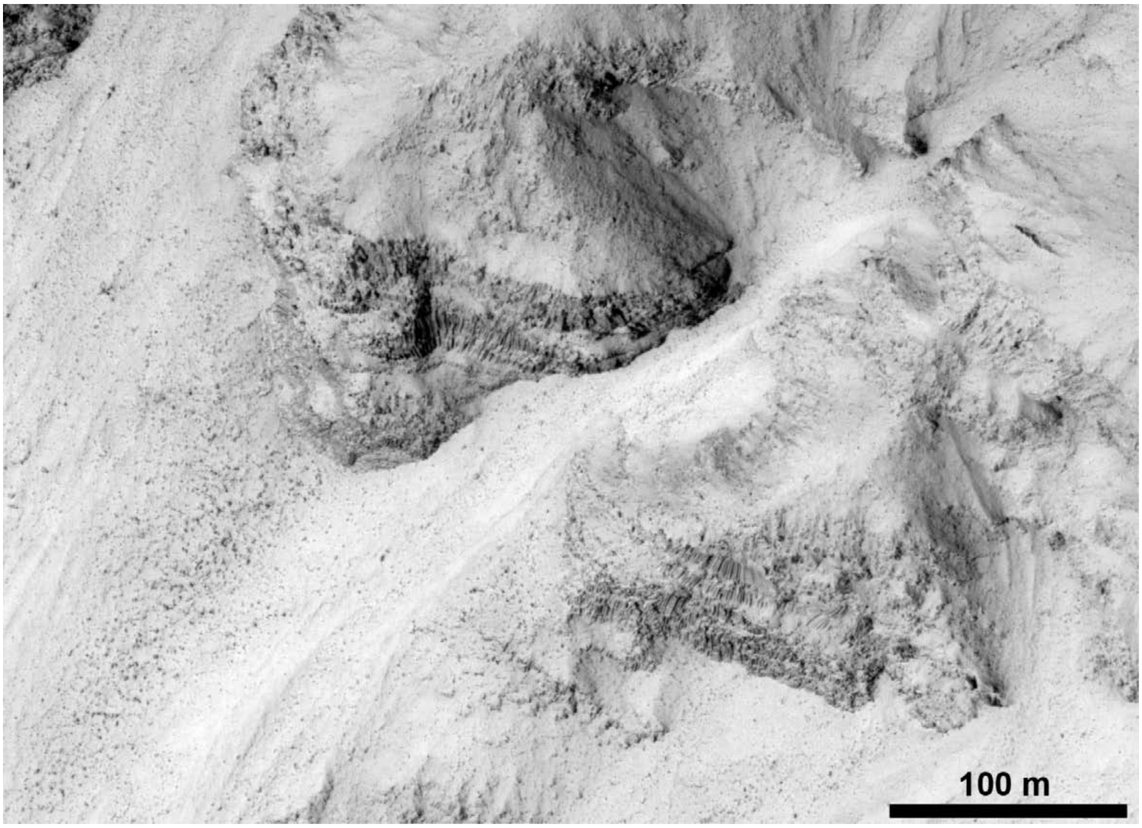

Fig. 15. Columnar jointed lava in Marte Vallis. Portion of HiRISE image PSP_007341_2020 centered at 21.644°N, 184.321°E. Multiple tiers of fanning columns are visible in lava flows exposed in the wall of an impact crater. This "entablature" style jointing is diagnostic of water-cooled lava (Milazzo et al., 2009).

define a set of kilometer-sized polygonal sections of crust that are often highly warped. Where the flow surface does not appear covered with sand and dust, it exhibits 1–10 m scale blocks. On lava flows, the kilometer-scale plates are bounded by either rift zones or pressure ridges (e.g., Keszthelyi et al., 2008). Polygons are typically some tens of meters across. HiRISE color provides yet another indicator that the viscous flow from Hrad Vallis is not a mafic lava flow. The bluer tones on this flow appear to be associated with trapped sands, rather than the flow material itself. Overall, HiRISE data strongly suggests that this flow was not lava and that a freezing mudflow is the most geologically plausible explanation.

A related feature type is strange collapse pits, sometimes with distinct ejecta (Morris and Mouginis-Mark, 2006). Some examples can be seen in HiRISE image PSP_006881_2145 and the stereo pairs composed of PSP_005879_2150 – PSP_005813_2150 and PSP_009742_2150 – PSP_010243_2150. The nature of the scale of the fracturing and warping of the material in these craters suggests that it had the same rheological and physical properties as the probable lahars. However, the topography visible in the stereo images shows that the fractures are dominantly radial tension fractures associated with collapse into the crater. Some of these features could be explained by dewatering of a wet deposit that filled a pre-existing impact crater. More volume loss would be expected in the center of the crater where the deposit would be the thickest. However, the radial ejecta from other craters indicates that, in at least some cases, there was an explosive removal of material. Morris and Mouginis-Mark (2006) suggest that this was caused by interactions between a hot mudflow and ground ice. The simple idea that they were formed by impacts into soft mud is not tenable because there are far too many of these 1–2-km-diameter craters to have formed in the time for a mudflow to have frozen (Morris and Mouginis-Mark, 2006).

3.3. Glaciovolcanic interaction

The evidence for interactions between volcanic eruptions and glaciers on Mars has been discussed since the Viking Mission (e.g., Allen, 1979; Hodges and Moore, 1979) and was reviewed by Smellie and Chapman (2002) and Head and Wilson (2007). Our discussion of HiRISE observations of these features is brief because, in most cases, the added resolution of HiRISE is unemployable due extensive modification of the surface at the 1–10 m scale. For example, there are curvilinear ridges in the aureole west of Pavonis Mons that have been interpreted to be moberg ridges, formed by subglacial fissure eruptions (e.g., Head and Wilson, 2007). The arguments based on earlier lower resolution data are not bolstered nor refuted by the HiRISE data because of extensive mantling. Similarly, there are a number of places where lava flows have unusually tall and steep margins. One possible explanation is that these were mafic flows that were confined by glacial ice (e.g., Head and Wilson, 2007). However, HiRISE has not resolved any features diagnostic of this process (e.g., vertically emplaced pillow lavas) largely because the flow margins are too degraded to preserve them. Alternative explanations for these flow margins include a viscous lava, lava flow inflation, and ponding against unconsolidated deposits that were subsequently eroded by the wind.

Perhaps the most commonly suggested class of glaciovolcanic feature on Mars is the tuya or table mountain (e.g., Smellie and Chapman, 2002). A group of potential tuyas and associated features in Chryse/Acidalia Planitia are discussed in detail by Martínez-Alonso et al. (submitted for publication). Features near the limit of HiRISE resolution can be debatably interpreted as pillows or hyaloclastite foreset beds and the CRISM data are consistent with magnesium- and iron-rich smectite clay, which could be derived from palagonite. The overall morphology and basic stratigraphy

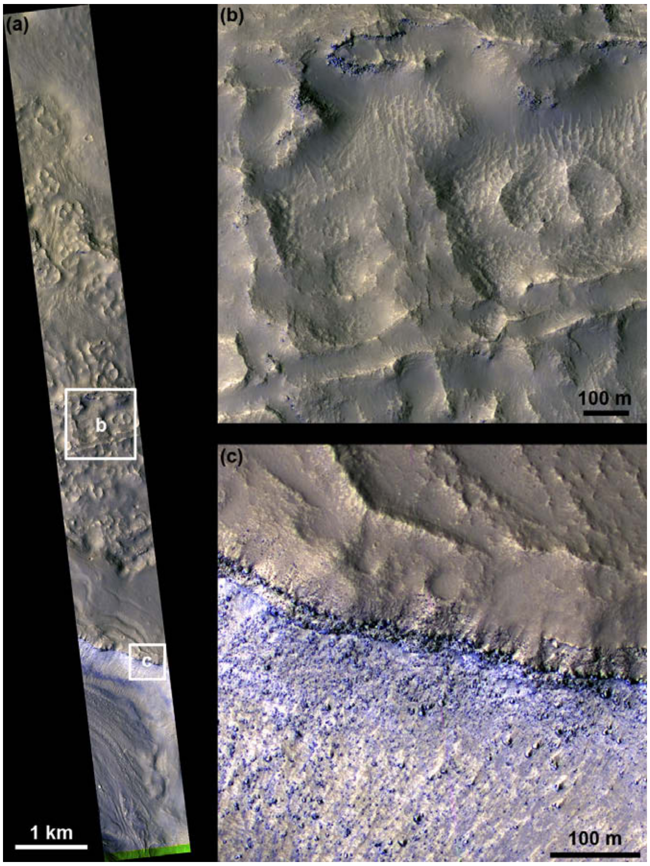

Fig. 16. Source region for Hrad Vallis. (a) Thumbnail of enhanced color strip from HiRISE observation PSP_010309_2145 centered at 33.961°N, 141.941°E. The head scarp for the channel system is at the southern end of the observation. (b) Close-up of disrupted materials on the flanks of the Elysium rise. This surface morphology is similar to other terrains interpreted to have been formed by the interaction of intrusive lava and (possibly ice-rich) sediment (e.g., Fig. 7c). In this case, a magmatic dike is suggested by the linear feature crossing diagonally across the lower part of the close-up. (c) Close-up of the walls of the scarp at the head of Hrad Vallis. The boulders with a blue tone, which is indicative of a mafic composition, appear to come from a few layers of competent rock near the top of the scarp.

of the Chryse/Acidalia mesas are consistent with formation by a subglacial eruption. However, the evidence is also consistent with other possibilities, such as an extended history of erosion and interactions between an ice-rich deposit and debris and/or lava flows (Martínez-Alonso et al., submitted for publication).

Despite the lack of definitive evidence for glaciovolcanic interactions in the HiRISE data, we wish to reiterate that there are many enigmatic landforms that may have formed by this process. As another example of an enigmatic feature of indeterminate origin, Fig. 18 shows part of Galaxias Mons, a distinct plateau in Utopia Planitia that has been interpreted as a moberg ridge (e.g., Chapman et al., 2000; Head and Wilson, 2007). This elongated rise connects to narrow ridges that are interpreted to be exhumed dikes. The HiRISE data show that the rise is surrounded by the same type of viscous flow that we interpret as likely lahars around Hrad Vallis (Fig. 18a). However, the surface of the rise is completely mantled or reworked and no primary features at the 1–10 m scale are evident (Fig. 18b).

3.4. Maars and tuff cones

Given the prevalence of volcanism and ground ice on Mars, explosive interactions during eruption, such as maars and tuff cones, would be expected (e.g., Carruthers and McGill, 1998). We

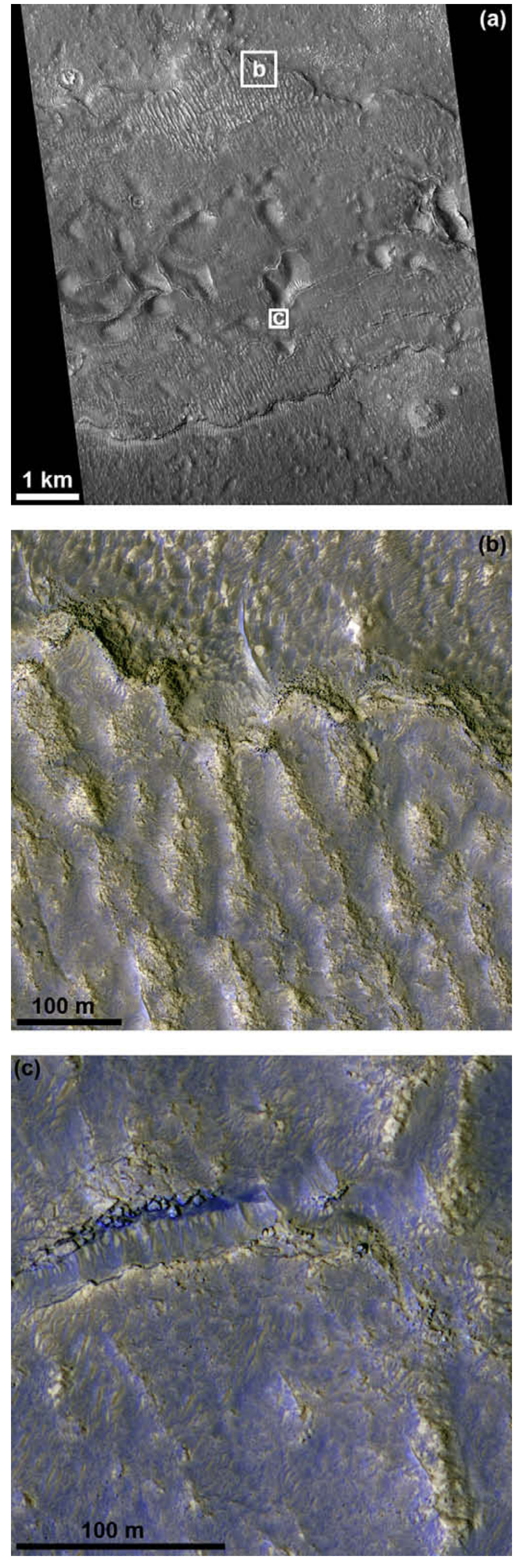

Fig. 17. Spillover from Hrad Vallis. Portion of HiRISE image PSP_007237_2140 centered at 33.85°N, 140.82°E. (a) Panchromatic overview of lobe of viscous material that spilled out of Hrad Valles and flowed across this scene from east to west. Note the corrugated surfaces near the flow margins and the buckled surface near the center. (b) Enhanced-color close-up showing the corrugated surface and boulders being shed from the flow margin. Aeolian bedforms are visible and are distinctly different from the corrugations. (c) Enhanced color close-up of buckled surface showing two different types of fractures, one separating kilometer scale areas and the other generating meter scale blocks. The dark bluish-gray (probably basaltic) sands appear to be accumulating in these fractures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

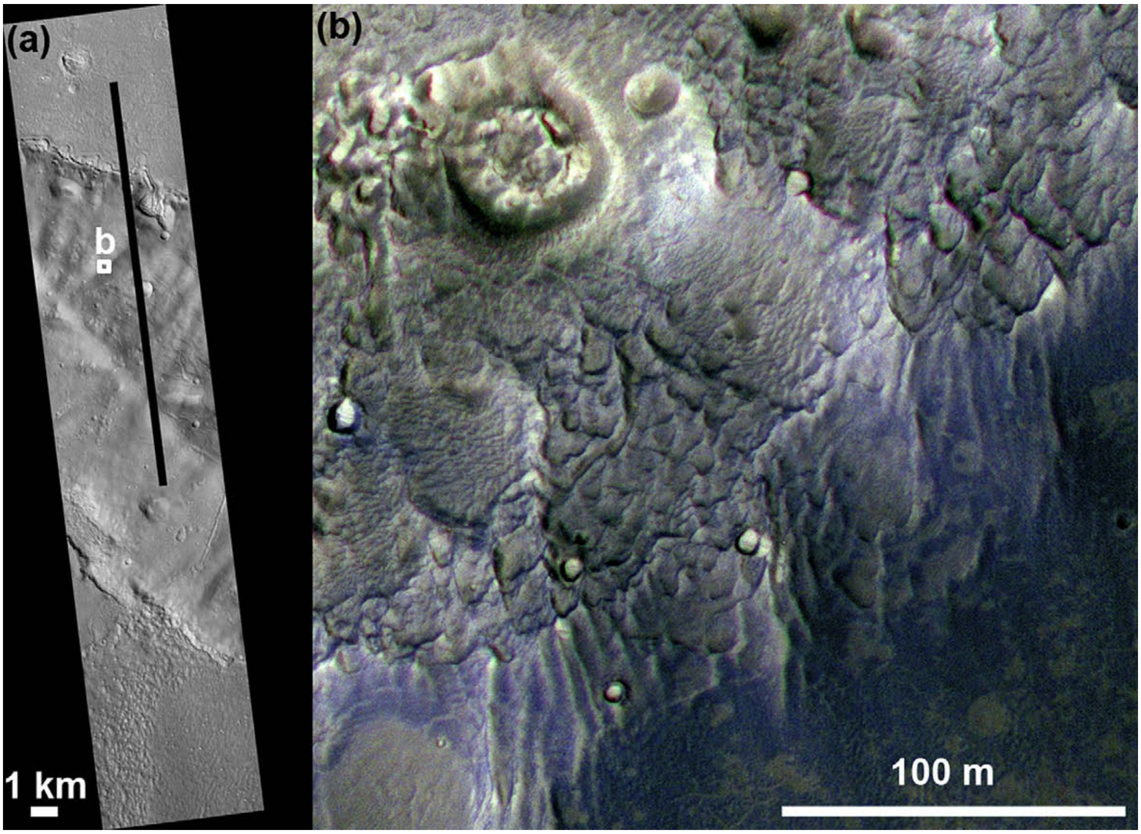

Fig. 18. Galaxius Mons, a potential moberg ridge in Utopia Planitia. (a) Panchromatic thumbnail of HiRISE image PSP_006670_2150 centered at 34.75°N, 142.32°E. The near-vertical black line in (a) is where data were lost during transmission to Earth. (b) Enhanced color close-up of a typical part of the ridge surface. HiRISE shows the area to be extensively modified at the 1–10 m scale by both impact and eolian processes, providing no additional evidence to support or refute the hypothesis that this ridge formed by a subglacial volcanic eruption.

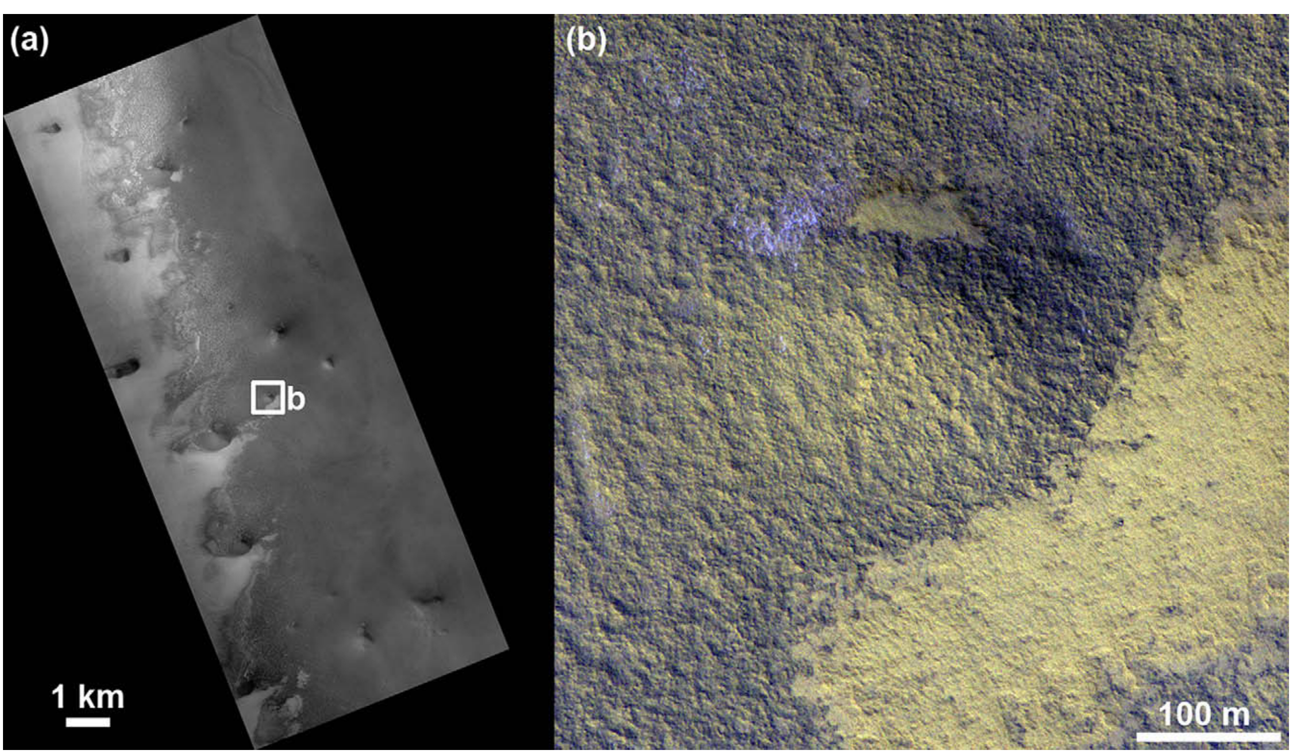

Fig. 19. Suggested north polar volcanic cones where interaction with permafrost is expected. (a) Panchromatic thumbnail of HiRISE image PSP_010316_2620 centered at 81.71°N, 288.28°E. (b) Enhanced-color close-up shows that these small mounds are too degraded to determine their origin. However, there is no evidence in this observation supporting a volcanic origin. The lack of even a remnant crater at the summit and the fact that other mounds in this observation have irregular shapes argue against volcanism having played a role in their formation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

have found no examples of craters that are suggestive of being a maar. However, it can be difficult to distinguish maars from modified impact craters. Similarly, there are cratered cones near the north pole that have been suggested to be tuff cones (Hodges and Moore, 1979). However, as shown in Fig. 19, there is no evidence in the HiRISE data that supports this interpretation. Instead, it is more likely that these are erosional remnants of older materials (Warner and Farmer, 2008). However, as with many of the glaciovolcanic interpretations, the heavily modified nature of these features at the 1–10 m scale does not allow us to point to strong evidence contrary to the tuff cone interpretation. Still, the detailed shapes of some of the mounds do not appear to be consistent with a tuff cone.

4. Conclusions

The spectacular increase in effective spatial resolution that HiRISE offers, supplemented by stereo imaging and color, has provided remarkable new insight into hydrovolcanic processes on Mars. However, looking at the global distribution of confidently identified hydrovolcanic features, the critical role of preservation is strikingly evident. The new insights have largely come from the single best-preserved (and presumably youngest) flood lava on Mars, in Athabasca Valles (Jaeger et al., 2007, this issue). Based on the examples from this flow, similar features can be recognized on slightly older equatorial flood lavas. However, as one moves back in time, the surfaces are too degraded to allow hydrovolcanic features to be recognized with confidence. At higher latitudes, where more near-surface ground ice is expected, there may be more opportunities for hydrovolcanism but this seems to be overshadowed by rapid cryogenic resurfacing. Similarly, the volcanics at high elevations on the Tharsis bulge are heavily mantled and features at the HiRISE scale that would be diagnostic of hydrovolcanism are difficult to identify. As with terrestrial fieldwork, finding good outcrops is an essential prerequisite to reaching robust conclusions.

The HiRISE observations from the Primary Science Phase show that liquid water ephemerally existed on, or near, the surface of the equatorial plains in recent (Late Amazonian) times. The evidence comes from both phreatovolcanic cones (Jaeger et al., 2007) and entablature-style jointing in lavas (Milazzo et al., 2009). While the most likely scenarios involve surface water, these features may have formed with only groundwater produced by the heat of the lava flows melting atmospherically implanted ground ice. Given the different implications for the current state of the martian hydrosphere, it will be important to differentiate these possibilities. Testing of the ideas with quantitative modeling is the next logical step.

The HiRISE observations also lend additional support to the idea of extensive flows of wet sediments, as mud volcanism and/or lahars. These processes have only been touched upon in a cursory manner in this study and we look forward to combining the HiRISE data with other data sets with broader coverage. Such work may have dramatic implications for the interpretation of the hydrologic and geologic processes in the middle part of Mars' geologic history.

While there is mineralogical evidence for interactions between volcanic rocks and aqueous fluids in the more distant past, it is unlikely that hydrovolcanic landforms have survived in a form that can be recognized in HiRISE images. Some questions may only be answered by future in situ missions.

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