INTERACTIONS BETWEEN ATHABASCA VALLES FLOOD LAVAS AND THE MEDUSAE FOSSAE FORMATION (MARS): IMPLICATIONS FOR LAVA EMPLACEMENT MECHANISMS AND THE TRIGGERING OF STEAM EXPLOSIONS

by

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Volcanic rootless constructs (VRCs), or rootless cones, have been identified in southwestern Elysium Planitia, atop the Athabasca Valles Flood Lava (AVFL), specifically within the Athabasca Valles outflow channel, Cerberus Palus, and the Aeolis Trough, an erosional valley north of Aeolis Planum. The Athabasca Valles Flood Lava is purported to be the youngest flood lava flow on Mars. Since rootless cones are formed from explosive interactions between lava and water/ice, the geologic history of the AVFL rootless cones is of great interest to the planetary community. This research expands on previous studies of AVFL rootless cones and extends the focus to include rootless cones in southern Cerberus Palus, as well as previously identified rootless cones in the Aeolis Trough. Observations of the two related, but morphologically differing cone fields within the AVFL, allows us to examine the emplacement history of the AVFL and the triggering mechanisms of steam eruptions. This study represents a defined piece of the puzzle involving the geologic history of Elysium Planitia and the role of volatiles on the surface of Mars.

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CHAPTER 1

INTRODUCTION

Cratered cones interpreted to be volcanic rootless constructs (VRCs), or rootless cones, have been identified in numerous locations on Mars, including regions east of Syrtis Major in Isidis Planitia (Ghent et al., 2012), Tartarus Colles between northern Elysium Planitia and southern Arcadia Planitia (Keszthelyi et al., 2010; Hamilton et al., 2010, 2011), southwest Amazonis Planitia (Fagents et al., 2002; Fagents & Thordarson, 2007; Keszthelyi et al., 2010), and southwest Elysium Planitia (Lanagan et al., 2001; Lanagan, 2004; Jaeger et al., 2007; Lanz & Saric, 2009; Keszthelyi et al., 2010; Noguchi & Kurita, 2015) (Fig. 1).

Rootless cones are landforms that that have been constructed by the deposition of excavated material following explosive interactions between lava and water, and are hence, 'rootless' or without conduits that are deeply rooted to sources of magma in the mantle or within the crust. The nature of these features was first established by Thorarinsson (1953), based on his analysis of Icelandic rootless cones, where they are also referred to as 'pseudocraters'. The generalized model is portrayed as follows (Fig. 2): as lava flows over a substrate containing volatiles, the volatiles are heated to a vapor phase, and steam is produced. The buildup of steam increases pressure beneath the lava flow and an explosion through the lava may result if the pressure of the vapor significantly exceeds a threshold pressure, determined by the overburden (lithostatic) pressure on the volatiles and the mechanical strength of the lava (Greeley & Fagents, 2001). When this occurs, the volatiles escape explosively, and depending on the efficiency of heat transfer, the eruption can excavate and entrain substrate material with overlying lava to create a positive relief construct made of tephra/spatter, often with a central summit crater and an apron of finely fragmented ash (e.g., Fagents et al., 2002). Rootless cones on Earth are produced when lava interacts with surface water, water-logged sediments, or ice. It is suggested that on Mars the creation of volcanic rootless constructs could involve a range of volatile sources, such as ephemeral aqueous water (e.g., Hamilton et al., 2011), atmospherically emplaced ground ice (e.g., Keszthelyi et al., 2010; Hamilton et al., 2011), or ground ice protected under a layer of desiccated regolith (e.g., Dundas & Keszthelyi, 2013).

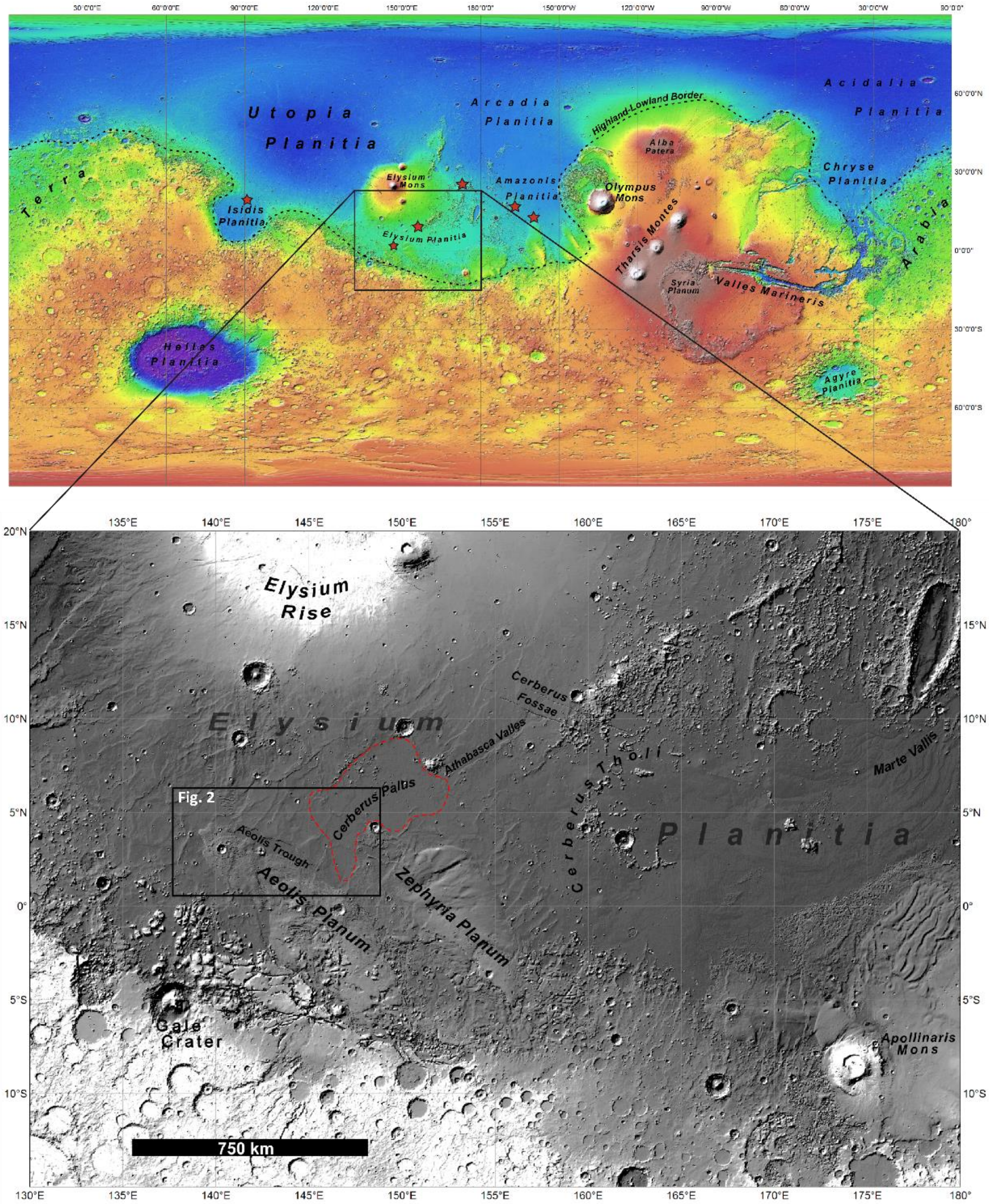


Figure 1. Top. Global map of Mars with nomenclature. Dashed line represents the hemispheric dichotomy border. Red stars represent locations of previously recognized volcanic rootless cones. Basemap is MOLA colorized terrain. 1 degree of longitude at the equator spans ~59.2 km. Bottom. Map of Elysium Planitia. The dashed red line is the generalized outline of Cerberus Palus. The black rectangle outlines the study region (shown in Figure 2). Medusae Fossae Formation (MFF) deposits here make up Aeolis and Zephyria Plana. Basemap is MOLA greyscale shaded terrain.

Many spectacularly preserved volcanic rootless cones (VRC) in Elysium Planitia have been identified in association with the Athabasca Valles Flood Lava (AVFL), which is hypothesized to have erupted from the Cerberus Fossae fissure system (Plescia, 1990, 2003) and be the youngest flood basalt lava on Mars (Hartmann & Neukum, 2001; Jaeger et al., 2010).

The study area is located in the southwestern portion of the Elysium Planitia Volcanic Province, within and adjacent to, a small, enclosed plain of lava referred to as Cerberus Palus (Fig. 1). The region of interest spans from ~137–149° E, 0–5° N with a total area of approximately 173,000 km^2 and is topographically constrained along the south and east by high standing plateaus, Aeolis and Zephyria Plana, composed of Medusae Fossae Formation (MFF) material (Tanaka et al., 2014) (Fig. 2). VRCs in Elysium Planitia have been observed in the Athabasca Valles outflow channel (e.g., Jaeger et al., 2007), within Cerberus Palus (e.g., Keszthelyi et al., 2010), and in an erosional trough north of Aeolis Planum (hereby referred to as Aeolis Trough) (e.g., Lanz & Saric, 2009).

The MFF is interpreted to be a fine grained pyroclastic deposit (Malin, 1979; Ward, 1979; Scott & Tanaka, 1982; Zimbelman et al., 1996, 1997, 2003; Tanaka, 2000; Kerber et al., 2008; Mandt et al., 2008) that is preserved in discrete lobes along the global hemispheric dichotomy border (Scott & Tanaka, 1986; Greeley & Guest, 1987; Zimbelman et al., 1996; Tanaka, 2000; Bradley et al., 2002). The MFF is typified by its ubiquitous yardangs (ridges formed by aeolian erosion) (Ward, 1979) and friable nature (Bradley et al., 2002; Mandt et al., 2007, 2008; Kerber & Head, 2010), and has been hypothesized to have high volatile contents in certain areas (Watters et al., 2007; Wilson et al., 2018). Putative large-scale water floods are proposed to have been discharged from Cerberus Fossae in association with and prior to flood lava eruptions (e.g., Plescia, 2003; Head et al., 2003). These water flood may have carved the Athabasca Valles channel system, debouching into Cerberus Palus (Burr et al., 2002), and possibly represent a source for recent volatile emplacement in Elysium Planitia.

This research project expands on previous conclusions regarding Elysium Planitia-AVFL rootless cones and includes cratered cones in the distal portion of Cerberus Palus and in the Aeolis Trough. Detailed observations of these related but morphologically differing cone fields in the AVFL, as well as lava characteristics, allow us to characterize the emplacement history of the AVFL and the triggering mechanisms of steam eruptions resulting in VRCs. I propose potential scenarios of volcanic rootless construct formation and examine how lava flow emplacement and the properties of the underlying substrate influenced the initiation of phreatomagmatic eruptions. Since rootless cones indicate explosive interactions between lava and relatively substantial amounts of volatiles, the presence of rootless cones on Mars is of great interest in the planetary community. This study represents a piece of the puzzle concerning the geologic history of southwestern Elysium Planitia, connecting the role of volatiles at the near surface and the lithological properties of the MFF.

CHAPTER 2

GEOLOGICAL CONTEXT

2.1 ELYSIUM PLANITIA

The study area is situated in southwestern Elysium Planitia Volcanic Province (Fig. 3 and 4), spanning from 137–149°E, 0–5°N. Elysium Planitia is the geographical name for the broad plain located approximately between 0° N-25° N and 140° E-180° E that is associated with the Elysium volcanic complex. The Elysium volcanic complex is centered at 25° N, 148° E and is comprised of the volcanic constructs Hecatus Tholus, Elysium Mons, and Albor Tholus (Mouginis-Mark et al., 1984). Elysium Planitia is largely covered by young lava flows that emanated from low shields and fissures (Lanagan, 2004). To the southeast of the Elysium volcanic complex are tectonic fissures that make up the Cerberus Fossae fissure system (see Fig. 1), which is believed to have acted as a conduit for massive outpourings of both lava and water (Burr et al., 2002; Plescia, 1990, 2003; Head et al., 2003; Jaeger et al., 2007, 2010). The Athabasca Valles Flood Lava (AVFL) is one such outpouring, that is interpreted to have erupted from the Cerberus Fossae approximately ≤.3 Gyr (Hartmann & Neukum, 2001), travelling through the Athabasca Valles outflow channel system previously carved out by aqueous floods (Burr et al., 2002).

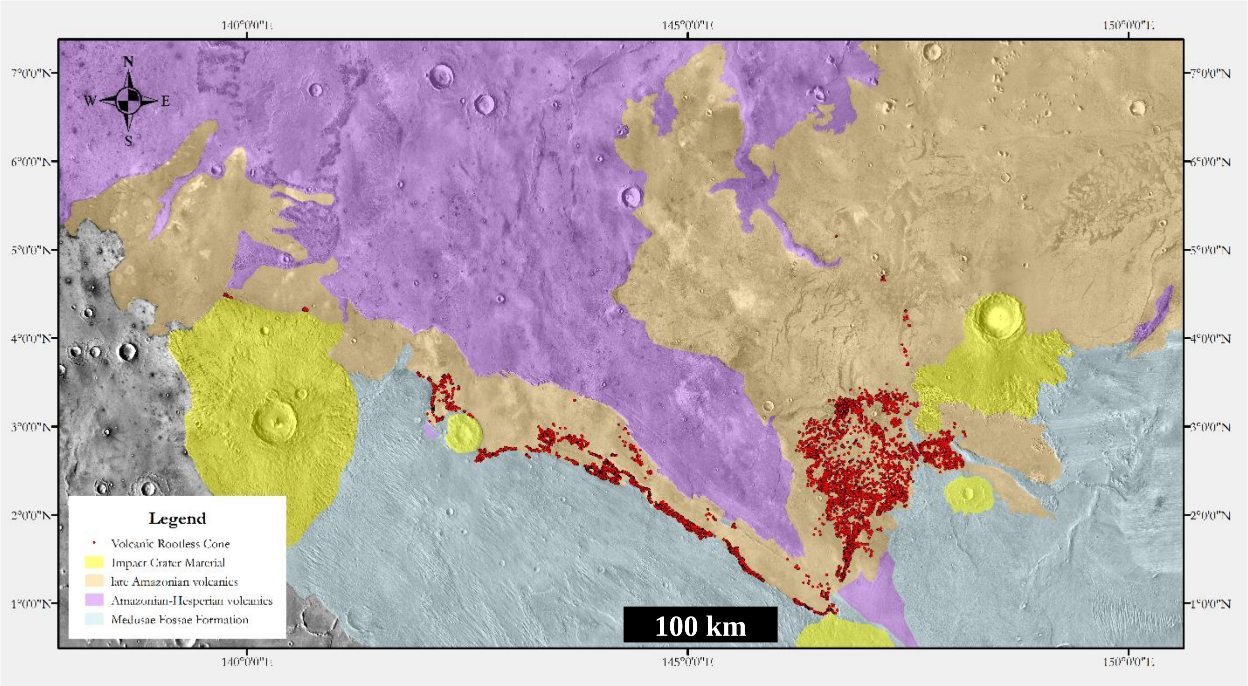


Figure 2. The study area encompasses the distal end of Cerberus Palus and an erosional trough north of Aeolis Planum, referred to here as the Aeolis Trough. The red dots represent individual volcanic rootless cones. Geologic units present are the Medusae Fossae Formation (MFF), Amazonian-Hesperian volcanics (AHv), and the Athabasca Valles Flood Lava (AVFL). Basemap is THEMIS Night IR. (Modified from Stacey & Kerber, 2017)

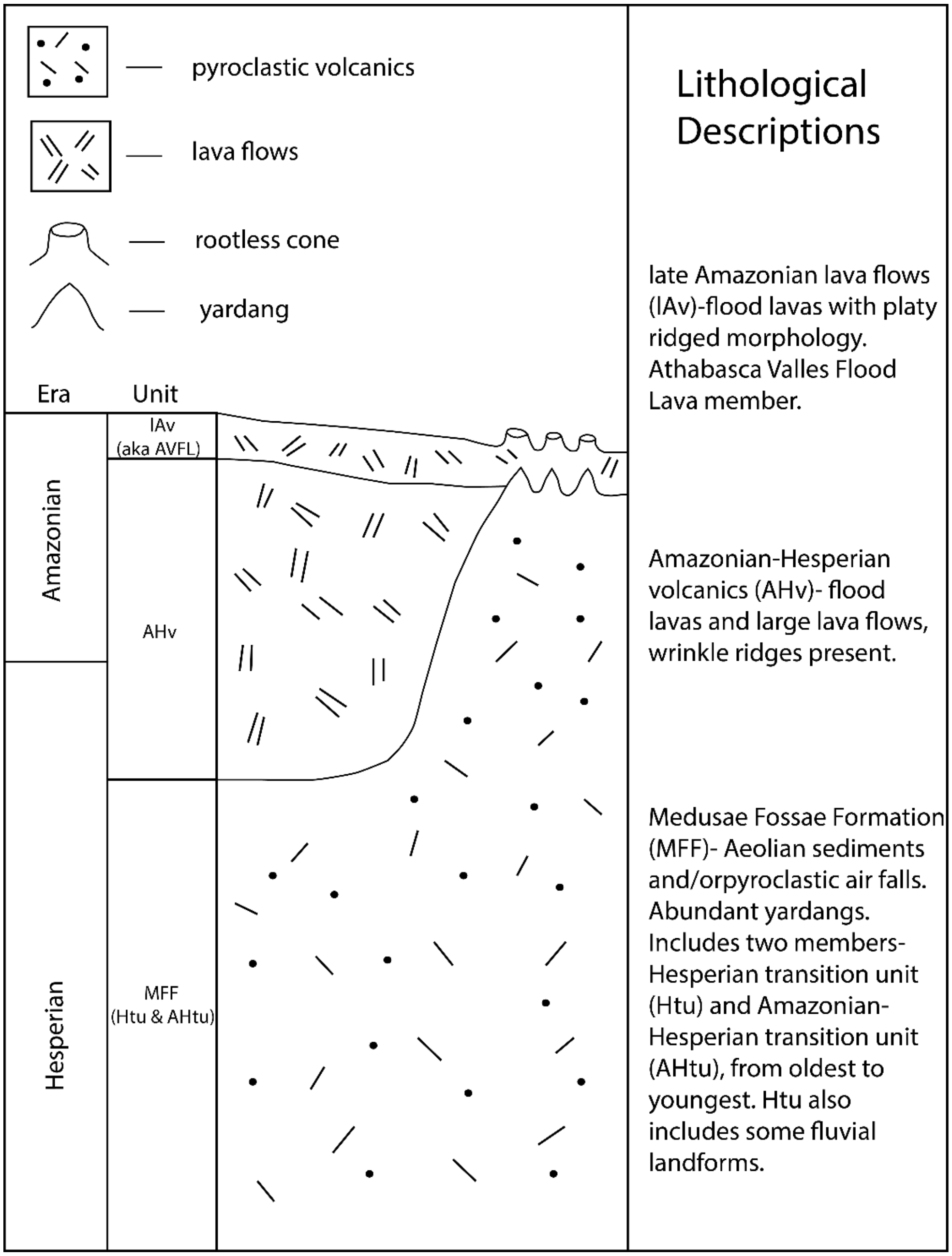
2.2 ATHABASCA VALLES FLOOD LAVA (AVFL)

The AVFL is known as the youngest and best-preserved flood lava flow on Mars (Plescia, 1990; Jaeger et al., 2007, 2010). This lava unit is typified by a 'platy-ridged morphology' initially described by Keszthelyi et al. (2000), due to the presence of large rough textured plates, ridges, grooves, and smooth, polygonal interplate material. The surface morphology has repeatedly been compared to the Icelandic Laki lava flow (e.g., Keszthelyi et al., 2004) and is characteristic of a rapidly emplaced, broad sheet flow, that developed a "thin crust translating atop a fluid interior" (Keszthelyi et al., 2000, 2010; Jaeger et al., 2007). This morphological expression of this type of lava flow emplacement has been explained by Keszthelyi et al. (2006), as forming due to "lava flowing under a thick disrupted crust that moves intermittently." The geological history of the AVFL has been interpreted as a single, brief fissure eruption from the Cerberus Fossae producing lava that flooded the downslope terrain, drained into the Cerberus Palus basin from the Athabasca Valles outflow channel, and ponded to form a lava lake (Jaeger et al., 2007, 2010).

The AVFL hosts numerous examples of hydrovolcanic constructs, most notably those found in proximal Athabasca Valles (Jaeger et al., 2007). These constructs, which have previously been referred to as ‘Ring Mound Landforms’, are volcanic rootless cones that display moats and wakes due to their formation on a thin, moving crust of lava (Jaeger et al., 2007).

2.3 MEDUSAE FOSSAE FORMATION (MFF)

The MFF is generally accepted as a friable, fine-grained unit of likely mixed pyroclastic and aeolian origins (Scott & Tanaka, 1982, 1986; Greeley & Guest, 1987; Zimbelman, 1997; Mandt et al., 2008; Kerber et al., 2011), hypothesized to have been deposited as a volcanic pyroclastic flow ignimbrite (Mandt. et al., 2008 and references therein). The eroded top of the MFF is characterized by ubiquitous wind-eroded aerodynamic ridges called yardangs which form due to the deflation of less resistant sediment layered with more resistant material, within a unidirectional wind flow regime (Ward, 1979). It is highly susceptible to intense erosion, modification, and redeposition (Scott & Tanaka, 1982, 1986; Greeley & Guest, 1987; Zimbelman, 1997) and this tendency to be preferentially eroded has made constraining ages problematic; Scott & Tanaka (1986) used crater counts to determine an Amazonian age (<3.0 Ga) for the MFF, but subsequent work revealed that there was most likely multiple episodes of deposition and redeposition, consequently, crater counting can only yield a minimum age of formation (Kerber & Head, 2010). The age of the MFF is typically regarded to be approximately mid-Amazonian, but there is not a clear division between original formation ages and redeposition ages; therefore, emplacement ages could have been as early as Hesperian (~3.7-3.0 Ga) (Kerber & Head, 2010; Zimbelman & Scheidt, 2012). Tanaka et al. (2014) divides the deposit into a lower ‘Hesperian transition undivided’ unit and an upper ‘Amazonian-Hesperian transition undivided’ unit, with the lower member exhibiting modification by fluvial activity. Because of the complexity of its depositional history, I do not attempt to divide the MFF into subunits.



late Amazonian lava flows (lAv)-flood lavas with platy ridged morphology. Athabasca Valles Flood Lava member.

Amazonian-Hesperian volcanics (AHv)- flood lavas and large lava flows, wrinkle ridges present.

Medusae Fossae Formation (MFF)- Aeolian sediments and/orpyroclastic air falls. Abundant yardangs. Includes two members- Hesperian transition unit (Htu) and Amazonian-Hesperian transition unit (AHtu), from oldest to youngest. Htu also includes some fluvial landforms.

Figure 3. Stratigraphic column of the geologic units in the area of interest. The stratigraphic units within the study area are 1. Late Amazonian volcanics (lAv), 2. Amazonian-Hesperian volcanics (AHv), and the 3. Medusae Fossae Formation (MFF) which is comprises an upper and lower member: Amazonian-Hesperian transition unit (AHtu) and Hesperian transition unit (Htu), respectively. The unit names are based on the USGS Geologic Map of Mars (Tanaka et al., 2014). Thicknesses of the units are lower limits and estimated based on MOLA derived vertical relief. Epoch absolute ages are based on those reported in Hartmann and Neukum (2001).

CHAPTER 3

MATERIALS AND METHODS

The methodology of this project integrates photogeological mapping done using ArcGIS software of the Cerberus Palus and Aeolis trough region, with morphological analyses of relevant landforms and geologic units. For basemaps, we utilize the MGS MOLA Mission Experiment Gridded Data Record at a resolution of 128 pixel/degree and the global Thermal EMission Imaging System (THEMIS) Nighttime IR mosaic. We also utilize a regional mosaic of Mars Reconnaissance Orbiter Context Camera (CTX) imagery that spans from 140-176 E and 0-12 N, with a resolution of 6 m/pixel. This mosaic was created by Jay Dickson at the Bruce Murray Laboratory for Planetary Visualization, using a non-destructive image processing technique (Dickson et al., 2018). CTX imagery was used for mapping of geologic units and for general identification of VRC candidates. HiRISE imagery was combined with the CTX mosaic to provide higher resolution observations at .3 m/pixel, which, depending on the size of the landforms, was necessary for further inspection of morphological characteristics.

The CTX mosaic was used to generate a 1:100,000 scale map of the major geological units in the study area. The global geologic map of Mars by Tanaka et al. (2014) was used as a reference for contact boundaries. The final map is presented in a Mars equidistant cylindrical projection using the D_MARS datum and an East positive geographic coordinate system.

Mapping of the VRCs was done in ArcMap by digitizing them as point features. Landforms identified as VRC candidates were selected for mapping using the following criterion, which has been modified by those outlined in Fagents et al. (2002): 1. Displays a distinct positive relief conical structure that is either circular, near circular, or ellipsoid in shape, 2. Contains a visible summit crater whose floor does not lie below the surrounding terrain, 3. Is superpositioned on, specifically, a lava or lava altered surface, 4. Does not extrude any volumetrically significant material.

CHAPTER 4

RESULTS

4.1 PHYSIOGRAPHY

There are two distinct localities within the study area where cratered cones are found: the Aeolis Trough and the distal end of Cerberus Palus. Within Cerberus Palus is the Athabasca Valles Flood lava (AVFL) and encompassing the southern part of the palus (or small plain) are two geological units: Amazonian-Hesperian volcanics (AHv) to the west and the Medusae Fossae Formation (MFF) to the east and south (see Fig. 1 and 2 for context) (Tanaka et al., 2014). The region of interest within the Cerberus Palus locality covers an aerial extent of over 18,000 km^2. The surface of this palus is relatively flat (the regional slope is measured by Lanagan (2004) to be ~.025°), with steeper slopes on the western margin, at the Amazonian-Hesperian volcanics and the Athabasca Valles Flood Lavas contact, and the eastern margin, at the Medusae Fossae and Athabasca Valles Flood Lavas contact (Fig. 4). The Aeolis Trough is an erosional valley formed via the removal of MFF material by aeolian action (Lanz & Saric, 2009; Kerber & Head, 2010), roughly 400 km in length and ranging from 2-60 km in width. The trough is bounded by a steep scarp of AHv on the northern side and a more gently sloping transition into the MFF on the southern side (Fig. 5). The Medusae Fossae is canonically characterized by its ubiquitous and massive yardangs, however, MFF yardangs at the northern margins of Aeolis and Zephyria Plana are more commonly eroded into smaller scale meso-yardangs, ~100-300 m in length (see Fig.7a, c, e). All cratered cones identified in the study area sit atop the Athabasca Valles Flood Lava (AVFL), which flowed through the Athabasca Valles outflow channel to the north and debouched into a topographic depression that formed the Cerberus Palus lava plain (see Fig. 1 for geographical context). The AVFL has a platy ridged surface morphology, as described by Keszthelyi et al. (2000), which is characterized by rafted slabs, or plates, of crustal material that fit together in a jigsaw puzzle pattern and interplate material of smooth, hummocky surfaces. These morphological characteristics of the AVFL indicate periodic surging and ponding of low viscosity lava, and the formation of a lava lake with a thin, cooled crust over still molten lava.

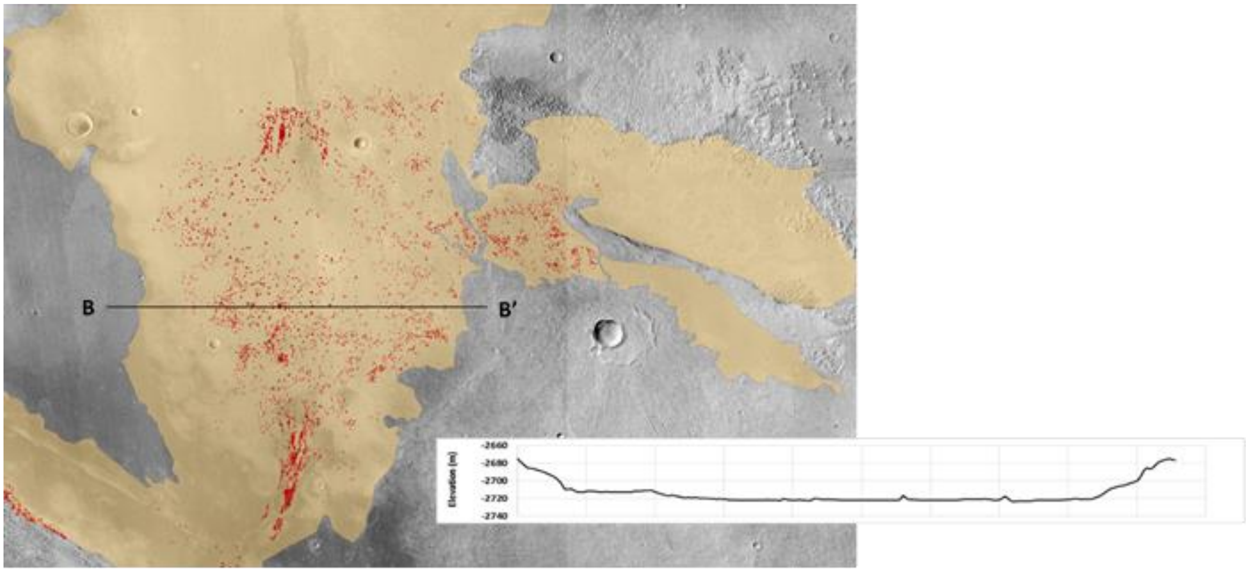


Figure 4. The Cerberus Palus lava lake. Red dots represent individual VRCs. The black line is the B-B’ topo line, which is 95.5 km in length. Basemap is a CTX imagery mosaic. Topographic profile is vertically exaggerated. North is up.

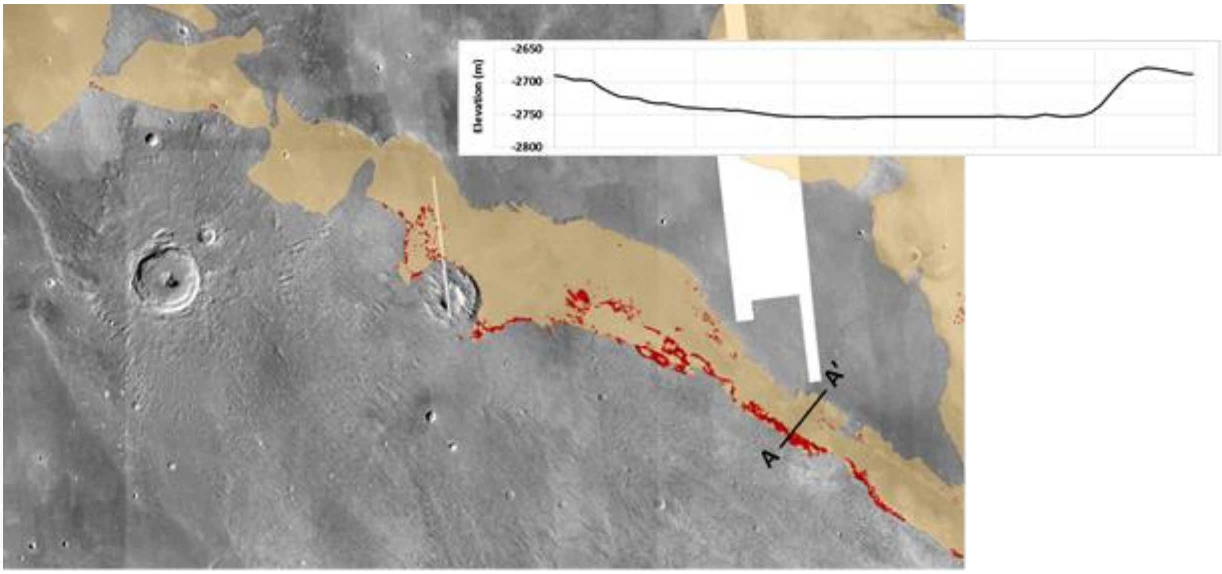


Figure 5. The Aeolis Trough erosional valley. Red dots represent individual VRCs. The black line is the A-A’ topo line, which is 32 km in length. Basemap is a CTX imagery mosaic. Topographic profile is vertically exaggerated. North is up.

It is believed that after the lava ponded for some time, the lava then spilled out of the distal end of Cerberus Palus, and continued as a contained flow out through the Aeolis Trough (Jaeger et al., 2007, 2010). This interpretation is supported by 'bathtub rings', which are remnants of solidified lava that became morphologically disconnected from the rest of the lava crust following drainage, observed at the margins of southern Cerberus Palus (Fig. 6) marking high stands of the lava surface. How much lava initially filled the lava lake is difficult to constrain due to unknown underlying topography and a lack of direct measurements. However, a pre-drainage flow depth of ~45 m and a post-drainage flow depth of ~30 m were estimated by Murray et al. (2005), based on heights of lava draped craters, which coincide with the current topographic depression of ~12 m in Cerberus Palus (Lanagan, 2004).

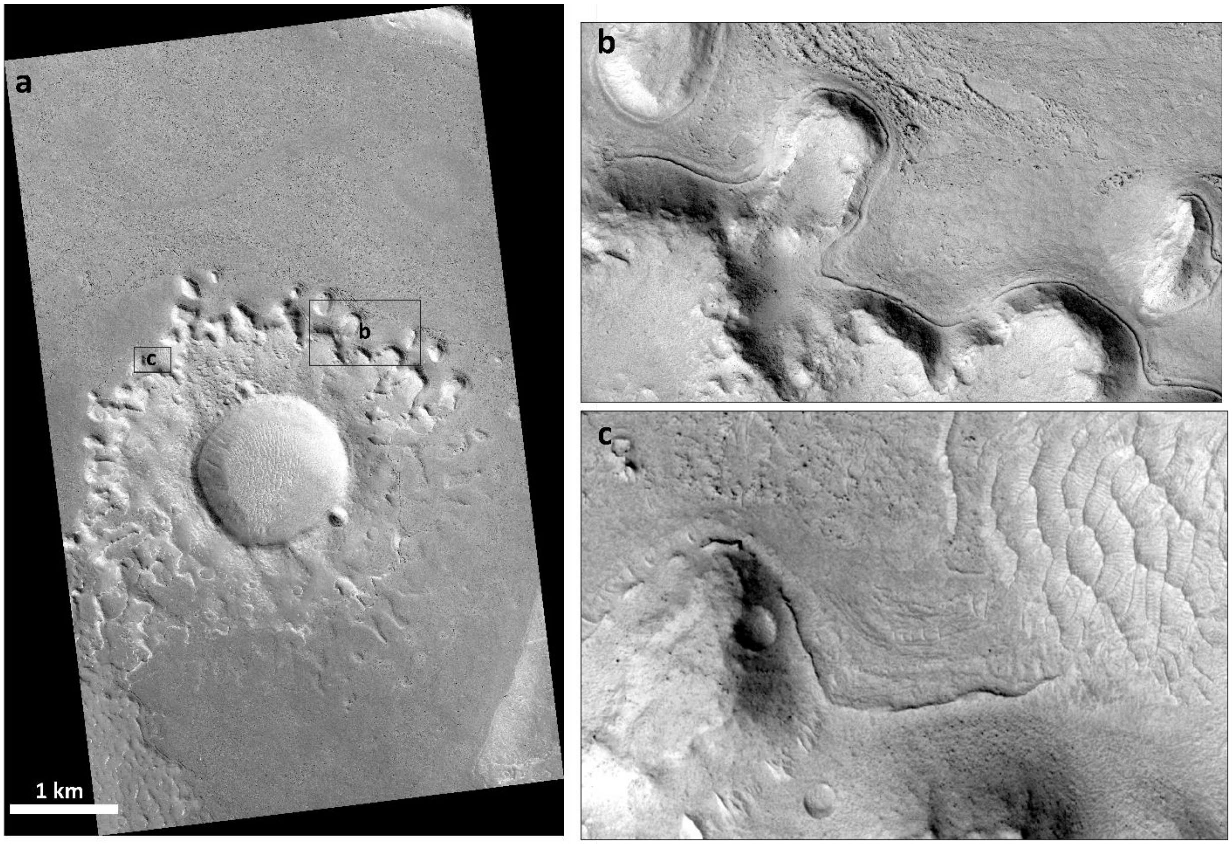


Figure 6. a) A lava embayed pedestal crater near the western margin of southern Cerberus Palus displaying bathtub rings around its plateau of high-standing ejecta. Boxes outline the insets in b and c. HiRISE image ESP_028928_1795. North is up. b, c) Close up images show thin terraces of cooled lava adhered to the plateau slopes, marking lava level high stands.

4.2 VOLCANIC ROOTLESS CONES

A total of 12,471 cratered cones were located and digitized; 6,801 in distal Cerberus Palus and 5,671 in the Aeolis Trough. Cratered cone sizes range from 4-140 m in basal diameter and 4-100 m in crater diameter, with ratios of crater to cone diameters ranging from .45-.7. Additional rootless cone fields might be present in other parts of Cerberus Palus, beyond the extent of this study's region of interest, but identification of which is largely limited by HiRISE imagery coverage, which is not uniform, and quite sparse, across Cerberus Palus. However, some outlying VRCs near the northern border of Cerberus Palus have been noted by Keszthelyi et al. (2010). Figure 7 shows the diversity of morphologies of hydrovolcanic landforms within this study's area of interest, as well as examples from other areas of Mars, together at the same scale. By examining the various morphological characteristics of VRCs, their spatial distribution, and context, I can understand what role the emplacement history of the Athabasca flood lavas and the lavas' interaction with the MFF played in their formation.

The cratered cones found within the Aeolis Trough show minimal degradation, are generally elliptical in shape, being oriented parallel to the direction of neighboring MFF yardangs (Fig. 7a) These elliptical cratered cones can have single summit craters or be present in elongate ridges with multiple or overlapping summit craters (Fig. 7a). Aeolis Trough cones are surrounded by aprons of light colored material, reminiscent of ash halos, and contain meter size boulders within their summit craters (Fig. 7a). There is a strong concentration of cones along the southern margin of the trough, where lava abuts Aeolis Planum, embaying and draping MFF material. Cratered cones in this region are located primarily within a ~5 km zone from the southern border (see Fig. 2). There are a few cratered cones along the northern margin of the trough, however, these cones are mostly located adjacent to remnant deposits of MFF. This spatial distribution has also been previously recognized by Lanz & Saric (2009). Very few cratered cones are found throughout the medial portion of the trough; these cones are more symmetrical in shape and also display aprons of light colored material (Fig. 7b). Transverse aeolian ridges (TARs), which are ripple-like aeolian bedforms possibly formed due to the redistribution of fines (e.g., Berman et al. 2018), are abundant within the Aeolis Trough, and are commonly found alongside groups of cratered cones.

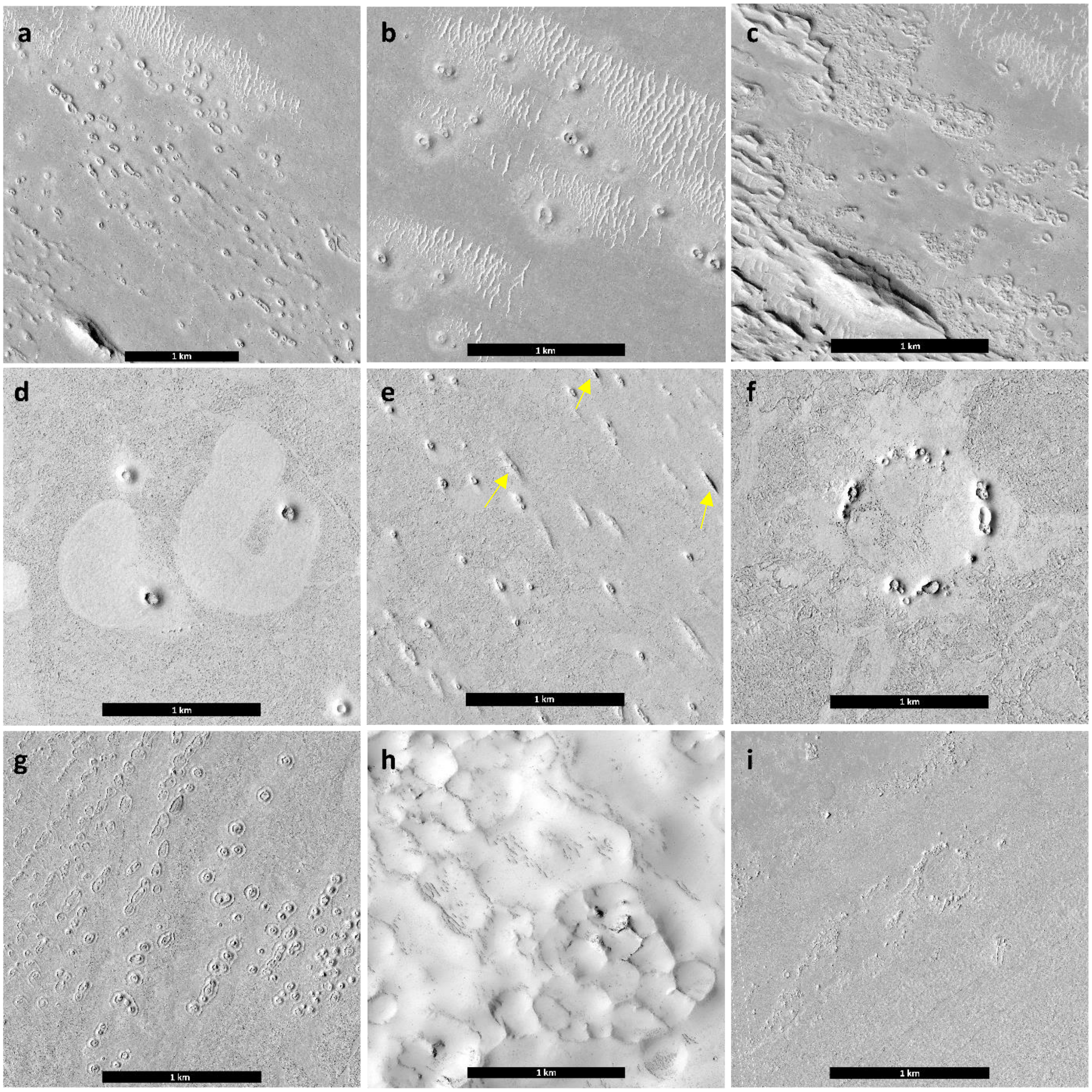


Figure 7. Gallery of VRCs and phreatic landforms found in study region (a-f) and in other areas of Elysium Planitia (g-i). In all images, north is up. a) Elliptical/elongate VRCs in the Aeolis Trough near the AVFL-MFF contact, where lava has draped the smaller, meso-yardangs, leaving a combination of lava covered mounds and cratered cones. The orientation of the VRCs is nearly uniform and parallel to yardang orientation. HiRISE image PSP_002622_1820. b) Symmetrical VRCs in the medial portion of the Aeolis Trough. Cones are surrounding by light colored material, interpreted to be ash aprons. Transverse aeolian ridges are present near cones, possibly comprised of eroded and redistributed MFF material. HiRISE image ESP_036220_1820. c) Pitted terrain adjacent to high-standing MFF material in the Aeolis Trough. Elliptical VRCs are present adjacent to areas of pitted terrain. HiRISE image ESP_ 013355_1815. d) Symmetrical VRCs in Cerberus Palus. Cones are enveloped by smooth, hummocky surfaces, interpreted to be pahoehoe lava.

Surrounding surfaces are rough and blocky, interpreted to be ‘a‘ā lava facies. The smooth terrain is lower than the rough terrain, so the pahoehoe is not inflated. Cones have steep, smooth walls, and meter sized boulders within their summit craters. HiRISE image ESP_037222_1820. e) Elliptical VRCs at the AVFL-MFF contact on the eastern edge of distal Cerberus Palus. Kipukas are also visible where lava has embayed some of the meso-yardangs, leaving islands of high-standing material (yellow arrows). HiRISE image ESP_054615_1820. f) VRCs atop impact crater rim in distal Cerberus Palus. Mostly symmetrical VRCs are found in circular groups, surrounded by smooth, hummocky surfaces, with slight depressions in the centers. These are interpreted to be rootless explosions that occurred at the tops of impact crater rims. Some cones have overlapping summit craters, making them appear elongated. HiRISE image ESP_046308_1825. g) VRCs in Athabasca Valles. The left half of the image shows cones with wake trails and the right half of the image shows cones with moats. These VRCs are aligned with the direction of lava movement which is to the southwest. HiRISE image PSP_001606_1900. h) Pitted terrain near Tartarus Colles VRCs. HiRISE image PSP_007605_2055. i) VRCs atop impact crater rim in Athabasca Valles. HiRISE image PSP_002147_1875.

There is an additional morphologically distinct phreatic-type landform located in the Aeolis Trough, which I have termed ‘pitted terrain.’ This pitted terrain is located at the bases of larger, marginal MFF yardangs, as well as amalgamated within groups of elliptical cratered cones. This landform is comprised of rimmed pits found in patches of higher standing terrain, presumably remnant MFF material, that were embayed by lava (Fig. 7c). These observations indicate that rootless eruptions occurred atop lava covered meso-yardangs and suggest that there is a relationship between MFF material and rootless cone formation, in agreement with conclusions made by Lanz & Saric (2009).

Within distal Cerberus Palus, there are three distinct morphologies of volcanic rootless constructs, separated by location, all displaying minimal degradation. Cratered cones were found primarily in the medial section, as well as at the eastern margin where lava abuts Zephyria Planum, embaying and draping MFF material. In the medial portion, cratered cones are symmetrical, with broad summit craters that are commonly filled with boulders eroding from the overhanging crater walls, indicating material strength consistent with competent, consolidated spatter. These symmetrical cones predominately display single summit craters, though there are cones with multiple, coalesced summit craters. All symmetrical cones are generally surrounded by smooth, light colored surfaces with hummocky texture, reminiscent of pahoehoe lava (Fig. 7d). Darker colored, rubbly surfaces, reminiscent of transitional a'a' lava encompass the cones and surrounding hummocky material. While it might appear that the light colored, hummocky material is some type of secondary flow, it lies below the adjacent rubbly surfaces, indicating it was not deposited on top of the adjacent lava surface.

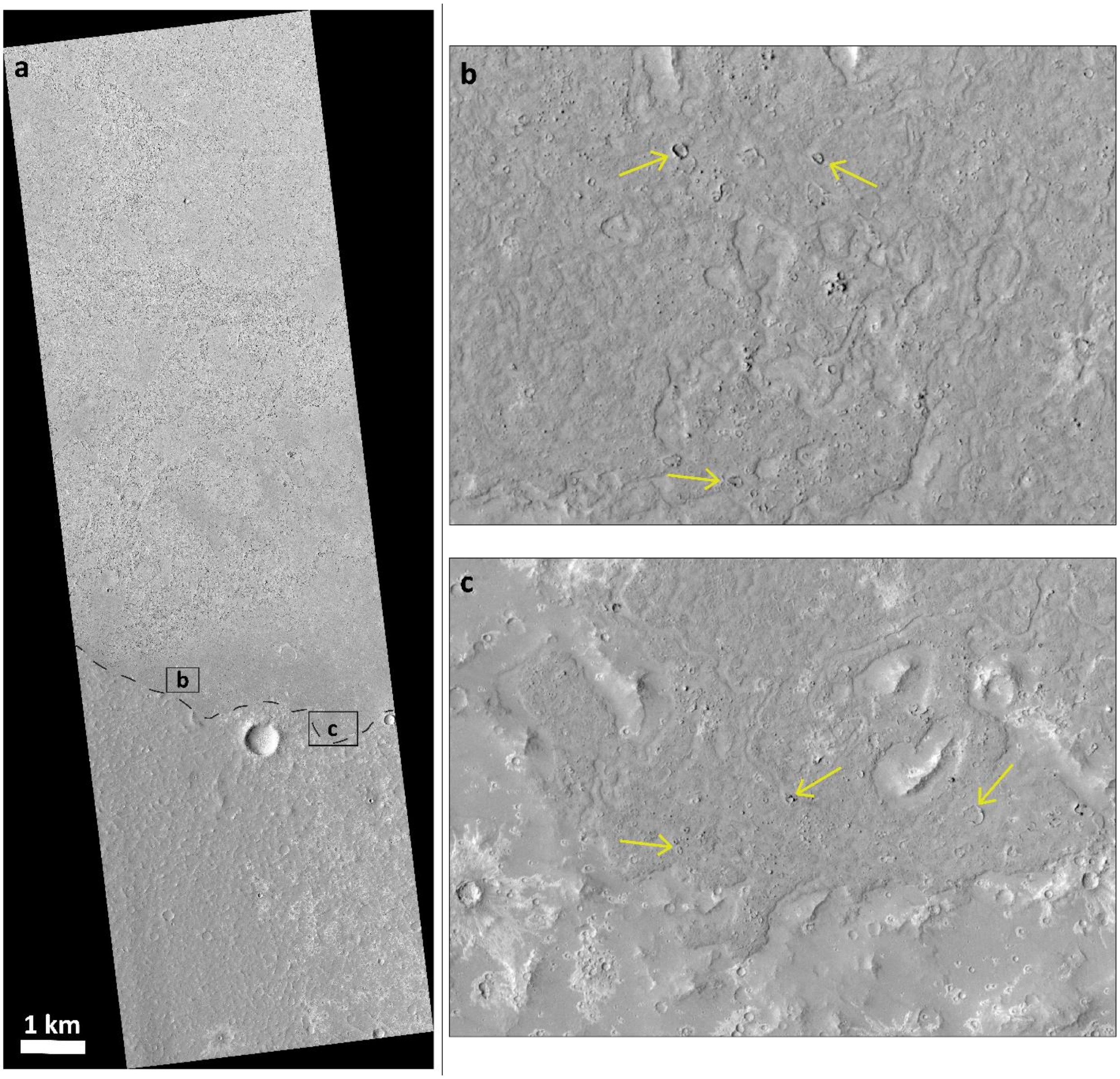


Figure 8. HiRISE image ESP_037710_1825. At the western margin of Cerberus Palus, where thin flows of lava drape the Amazonian-Hesperian volcanics substrate, there are small, thin-rimmed, circular constructs. There is no indication of ash ejecta or fragmented substrate material. The black line represents the contact between Amazonian-Hesperian volcanics and the Athabasca Valles Flood Lavas, and the arrows point to examples of these thin rimmed rings.

On the eastern margin of southern Cerberus Palus, cratered cones exhibit the same characteristics as those in the Aeolis Trough: elliptical shape and orientation parallel to neighboring MFF yardang directions (Fig. 7e). On the western margin, at the contact between AHv and AVFL, there are thin-rimmed constructs, reminiscent of spatter cones, up to a couple meters in diameter. These 'thin-rimmed rings' are much smaller than the cratered cones present elsewhere in the study area, only up to a couple meters in diameter, and are characterized by hollow, positive relief circular rims, rather than conical mounds with summit craters whose floors lie above the surrounding lava. (Fig. 8). The walls of these thin-rimmed rings seem to be composed of competent material, with high crater wall slopes. While these features are too small for accurate height measurements, their width to height ratio appears is quite large.

CHAPTER 5

INTERPRETATIONS

5.1 LAVA FIELD EVOLUTION- “FILL AND SPILL”

I interpret the emplacement and evolution of the lava flow to be analogous to the “fill and spill” style, outlined in Hamilton et al. (2015) and Hamilton (2018), which is comparable to the 1974 eruption of Kilauea. I propose the following model of AVFL lava field evolution:

Phase 1 – The Cerberus Fossae fissures erupted pulses of low viscosity lava that traveled through the Athabasca Valles outflow channel and advanced into a confined basin, Cerberus Palus.

Phase 2 – The lava filled the topographic depression within Cerberus Palus, where it developed into a ponded lava lake with a cooled, brittle crust and molten interior. Periodic surges of new lava raised the surface level and disrupted some of this crust, leading to rafted plates of crustal slabs and intraplate molten lava brought to the surface by extension of the plates or as compressional squeeze ups (Fig. 9). Cooling and contraction of the crust also acts to further subdivide the plates. During this stage, the narrow channel at the southernmost border of the lava lake developed marginal levees from stationary lava which acted as a dam, causing a backup of lava.

Phase 3 – Lava continued to flow into Cerberus Palus until it eventually spilled over the southern levées, resulting in drainage of the lava lake and lowering of the surface level, evident by ‘bathtub rings’ at the flow margins (see. Fig. 6). Lava was then fed through the narrow channel at the most distal reaches of Cerberus Palus, debouched, and transported through the Aeolis Trough, where it was directed around existing topography until it finally ponded within a smaller depression northwest of Aeolis Planum (see Fig. 2).

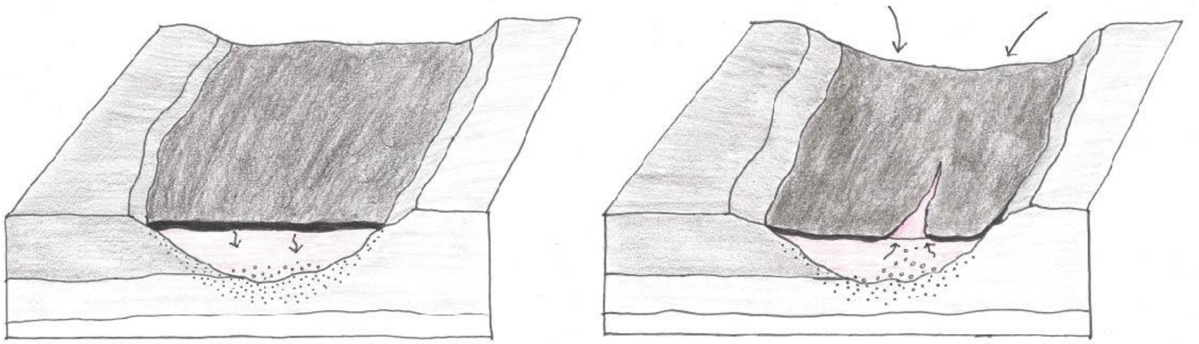


Figure 9. (Left) The AVFL fills the palus and ponds. A chilled crust forms around a molten interior, which becomes thickest at the edges of the margins of the flow front, where the lava is thinnest. Heat is transferred to the substrate and subsurface volatiles become supercritical fluids. The volatiles are not able to escape because the overlying pressure of the lava is too great. (Right) Once the lava is able to drain, the surface level lowers, leaving bathtub rings of lava crust at the margins. The brittle crust breaks into plates and molten lava between the plates reaches the surface where it cools and forms pahoehoe type lava. The depressurization from the lava drainage allows for the volatiles to become vaporized. Vaporization results in expansion of the gases, a volume increase, and finally, a rootless explosive eruption.

5.2 LAVA-SUBSTRATE HEAT TRANSFER/TRIGGERING OF STEAM ERUPTIONS

Rootless cones are normally formed by the sudden vaporization and explosion of substrate volatiles as they come into contact with hot lava. On the Earth, this occurs where lava can thoroughly mix with water, such as in lakes or marshes. The triggering of a rootless eruption may either involve an initial phreatic explosion, generated as a lava flow moves over a substrate containing a volatile coolant, heating the volatile to a vapor phase (Thorarinsson, 1953). Alternatively, a destabilization event at the base of the lava may cause intimate mingling of lava and water to produce a phreatomagmatic explosion (Fagents & Thordarson, 2007), analogous to molten–fuel coolant interactions (MFCIs), which are well-studied in the laboratory and by industry (Wohletz et al., 2013, references therein)

On late Amazonian Mars, we would expect any groundwater to be frozen, although, at the current obliquity and atmospheric pressure of Mars, even frozen groundwater should not be stable at the surface between ~±40° latitude (e.g., Mellon & Jakosky, 1993). For this reason, there has been some controversy over whether rootless cones can still be created in the absence of immediate intimate mixing between lava and water (Greeley & Fagents, 2001; Dundas & Keszthelyi, 2013), and instead created via steam build-up under a lava flow as the lava's heat melts the ground ice (Dundas & Keszthelyi, 2013). The presence of a thick layer of ponded lava with a molten interior insulated by a chilled crust would result in prolonged heating of the substrate, with heat reaching volatiles at greater depths than if a thinner flow was involved. The pressure exerted by this lava lake would act to increase the overburden pressure and thus, the boiling temperature of the volatiles. If the lava lake created in Phase 2 (described in 5.1) was thick enough, it might prevent near surface volatiles from becoming vaporized, leaving them in a supercritical state. Once the lava lake drained into the Aeolis Trough, the release of pressure would have allowed the supercritical volatiles to vaporize, rapidly expanding further, and reach the surface in an explosive eruption. This framework would explain why rootless cones are often found on the rims of buried impact craters (see Fig. 13): the peaks of underlying topography are where the lava flow is thinnest, and where the substrate volatiles can most easily vaporize and break through the overlying material.

Cerberus Palus cones are not observed to be deformed by the host lava and lack the downstream wake trails commonly associated with rootless cones in Athabasca Valles, indicating that the rootless cones in southern Cerberus Palus were not formed on a moving lava surface (Jaeger et al., 2007, 2010; Keszthelyi et al., 2010). Additionally, the Cerberus Palus cones lack the moat structures common around Athabasca Valles cones, indicating that they did not form atop a thin, brittle crust (Jaeger et al., 2007). Figure 7g and 7i show the cratered cones in Athabasca Valles and their distinct morphologies. The lack of moats and the presence of the smooth, hummocky surfaces that surround Cerberus Palus cones indicate that they formed within the weaker interplate lava that was exposed following of the crust. Therefore, I interpret the symmetrical VRCs within the lava lake to have formed after drainage of the ponded lava, once molten lava from the interior was able to reach the surface after disruption and breakup of the brittle crust.

5.3 FORMATION MODELS FOR VOLCANIC ROOTLESS CONES

The case of the yardang rootless cones is an unusual one. As outlined above, rootless cones should be more likely to form at underlying topographic highs. In this case, the presence of cones on the peaks of buried yardangs is not unexpected and could be linked to the thinness of the overlying layer. However, also visible are some yardangs with rootless cones on top which are embayed around the sides but not overtopped by the lava, as well as the pitted terrain lying above the lava surface. This means that the steam created by the heat of the lava interacting with the subsurface volatiles had to travel up through the yardang to explode. This transport may be possible due to the MFF's unusually low density and porous nature (see Section 5.4). Thus, in the case of the yardang VRCs, I interpret these to have formed due to lateral transport and buoyant accumulation of steam towards the buried yardang highs, where the volatiles became pressurized and exploded through the yardang hull cap rock and overlying lava. These energetic explosions led to the creation of wide cratered cones and highly fragmented ejecta (Fig. 10).

The buildup of pressure beneath the hull's resistant capping layer would have allowed for greater excavation and incorporation of the MFF substrate, which is evident, at least in the Aeolis Trough, by the abundance of transverse aeolian ridges and light toned aprons of material surrounding many of the cratered cones there. Elliptical VRCs on the eastern margin of southern Cerberus Palus do not seem to display this same degree of fragmentation or redistribution of fine-grained material. A possible explanation is that steam eruptions atop yardangs here were not as explosive as the steam eruptions atop yardangs in Aeolis Trough. Lava thickness appears to have been greater in the trough than at the eastern margin of southern Cerberus Palus due to the fact that many meso-yardangs in the latter region (even some of the smallest meso-yardangs) form kipukas (see Fig. 7e), while many meso-yardangs in the former region are draped by lava that seems to have deflated to some degree (see Fig. 7a). This indicates that there would have been greater heating of the substrate and accumulation of steam in Aeolis Trough than on the eastern margin of southern Cerberus Palus.

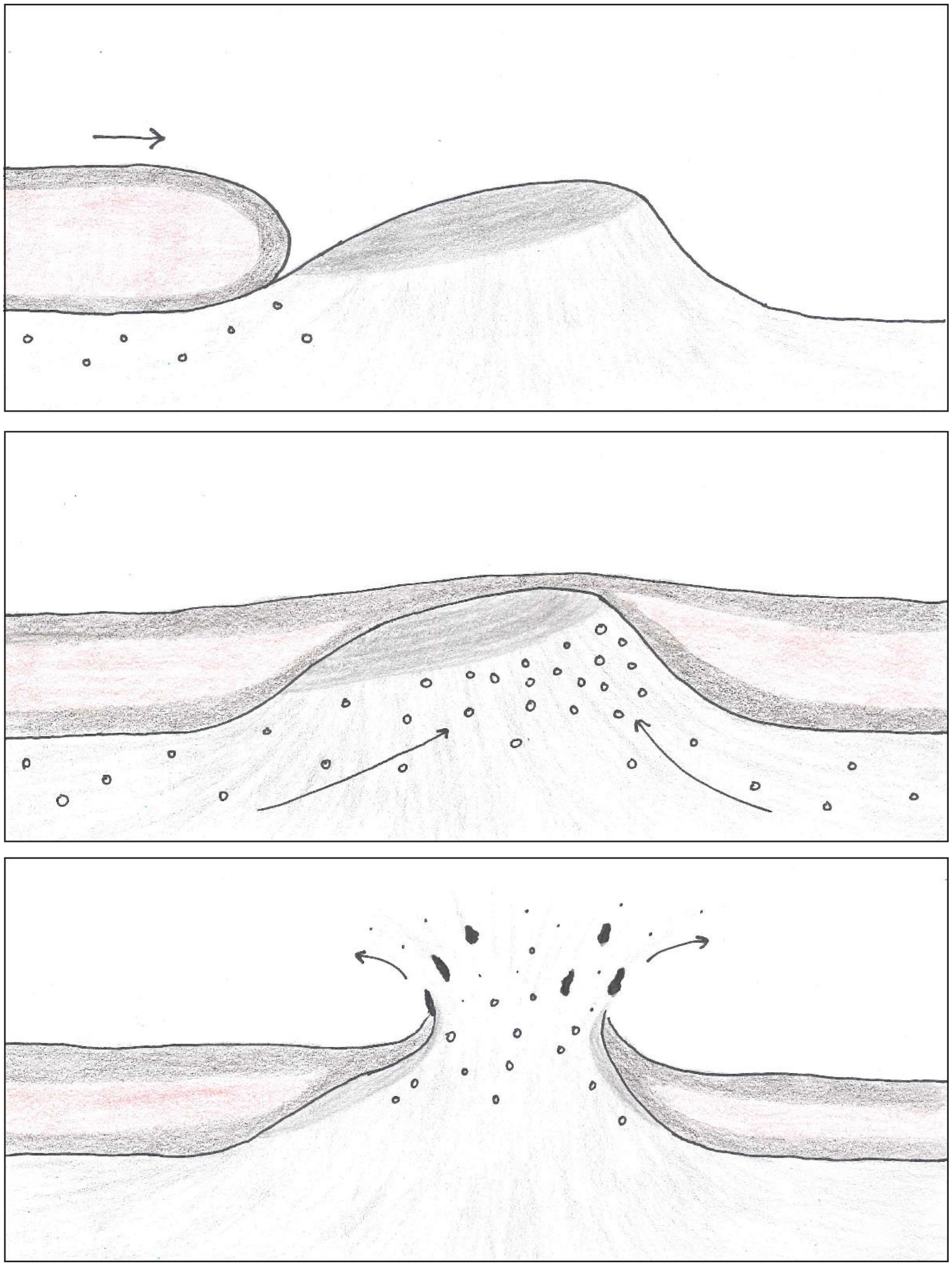


Figure 10. Eruption dynamics at yardang explosion sites. (Top) Lateral movement of volatiles through MFF material towards the meso-yardang highs (represented by black arrows). Expanding gas gets trapped beneath the competent capping layer of the yardang hulls, increasing the pressure. (Bottom) Once the pressure of the expanding volatiles exceeds the pressure exerted by the overlying material, an explosive eruption occurs, distributing fragmented particles of MFF yardang material and lava.

Due to the lack of moats/wakes and the presence of surrounding hummocky lava, southern Cerberus Palus cones must have formed after drainage of the lava lake, indicating the need for depressurization to allow vaporization (Fig. 11). The larger cratered cones in Athabasca Valles, that do not display moats or wakes, are interpreted by Jaeger et al. (2007) to have also formed due to reduction in lithostatic pressure following lava drainage. The smooth, hummocky terrain that encompass Cerberus Palus VRCs and lie below adjacent rubbly plates suggests that the crustal slabs within the lava lake were too thick to allow the escape of steam through them, directing the steam towards interplate areas instead. The spatial distribution of VRCs in southern Cerberus Palus is seemingly random, with no clear alignment of cones along subsurface structures (apart from the VRCs atop impact crater rims, see Fig. 7f). The locations of individual VRCs in southern Cerberus Palus was likely influenced by a combination of factors, such as the underlying topography, varying volatile availability, and lava crust geometry. It is possible that subsequent, repeated explosion cycles could have occurred due to infilling of lava at the explosion sites and intimate mixing of lava with the substrate. However, confirmation of repeated explosion cycles is dubious without field analyses of individual VRC stratigraphy, and the processes following the triggering of the steam explosions and incipient cone building is beyond the scope of this study.

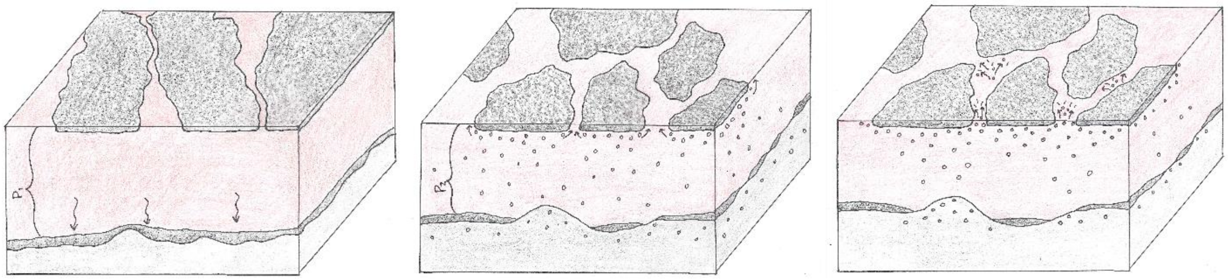


Figure 11. Formation schematic for symmetrical VRCs within medial southern Cerberus Palus. (Left) During ponding, the lava formed a chilled crust at the surface and at the lava-substrate interface. Periodic surging of lava increasingly fills the lava lake and disrupts the chilled crust, breaking it into large slabs. Cooling and contraction of the crustal slabs leads to further subdivision of plates. Heating of the substrate by the molten lava is indicating by the arrows. P_1 represents the overburden pressure at this stage. (Middle). As the lava lake begins to drain, a decrease in overburden pressure, represented by P_2, leads to depressurization and vaporization of substrate volatiles that were previously left in a supercritical state. (Right). Following depressurization, vapor begins to escape through the substrate, becoming exsolved in the molten lava interior and accumulating/coalescing under coherent crustal slabs (Ryan & Christensen, 2012). Once enough pressure has built up in the molten lava and under the crustal slabs, the vapor is directed towards

lower yield strength interplate areas where it escapes explosively (indicated by arrows), constructing cratered cones composed of welded tephra and spatter.

The thin rimmed cones found along the western flow margin of Cerberus Palus were probably formed in a manner analogous to ‘bubble bursts’ (Mattox & Mangan, 1997; Boreham et al., 2018), in which passive volatile escape occurs through the thin lava near the flow margins (Fig. 12). These eruptions were less energetic and did not result in excavation of substrate material.

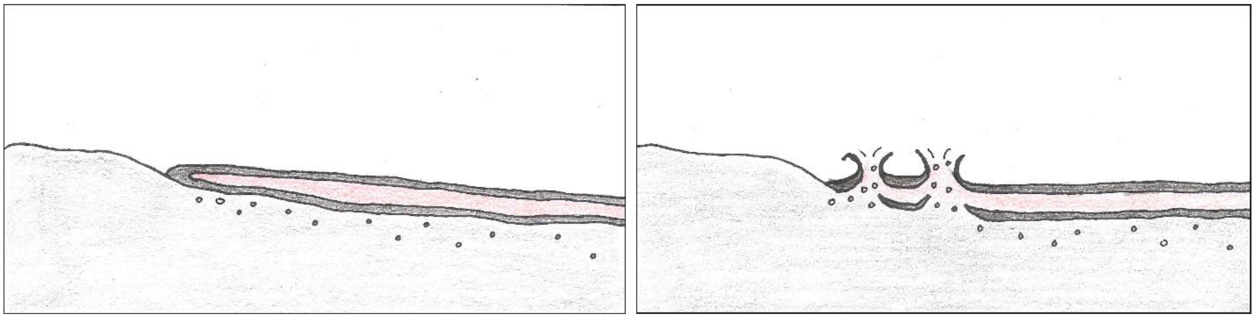


Figure 12. Small scale rootless eruptions result in thin rimmed constructs composed primarily of spatter. Smaller rim constructs form at the flow edges due to lower overburden pressure and accumulation of steam upslope, toward the flow edge.

Rootless cones atop lava draped crater rims represent a more traditional product of rootless eruption dynamics (Fig.13). Since the weight of the overlying lava is least at the high points along the crater rim, volatiles are more likely to escape explosively there, where overburden pressure is at a minimum (Jaeger et al., 2007). Faulting or fracturing along crater rims could also potentially lead to the development of heat pipe conditions and play a role in the transport of volatiles.

The pitted terrain along the margins of the lava in Aeolis Trough is more enigmatic. A landform of the same name has been observed near VRCs in southern Arcadia Planitia by Keszthelyi et al. (2010) (see Fig. 7h). While the pitted terrain in southern Arcadia Planitia is very similar to the pitted terrain in Aeolis Trough, the former is much larger and is also bordered by arcuate ridges that indicate uplift of the surface (Keszthelyi et al., 2010). I propose that Aeolis Trough pitted terrain is somewhat analogous to southern Arcadia pitted terrain, in that both are influenced by the “loss of volume in an unconsolidated layer” (Keszthelyi et al., 2010), however, Aeolis Trough pitted terrain does appear to have a constructional origin to some degree, unlike the latter. A possible, though somewhat ambiguous, explanation is that the pitted terrain is a by-product of hydrothermal venting, which is proposed by Lanz & Saric (2009) to have occurred along the Aeolis Trough, in which indirect heating of embayed MFF material led to lateral transport of steam and possible heat pipe conditions. Lava embayed remnants of higher standing, semi-unconsolidated MFF material acting as conduits for escaping steam could have allowed for small scale eruptions, excavating some proportion of MFF material to construct rimmed pits.

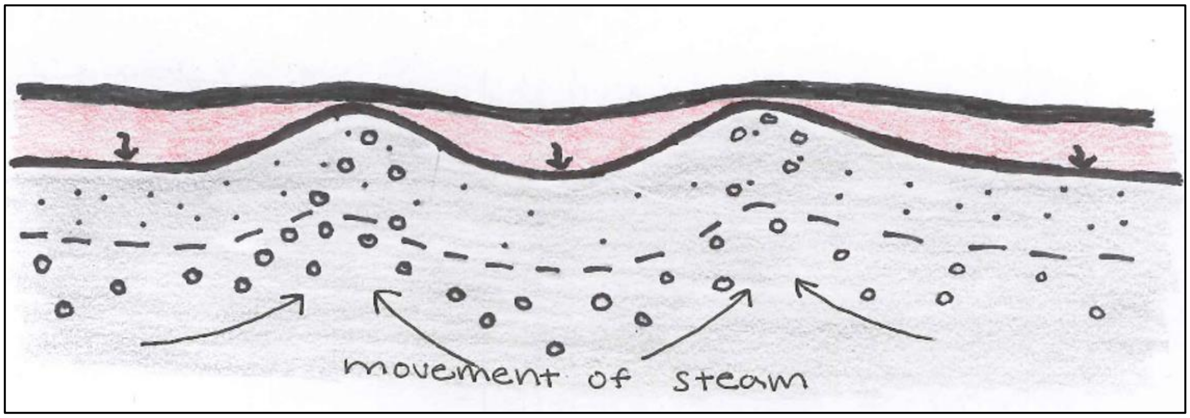


Figure 13. Eruption dynamics at impact crater rims. Small arrows represent heat flow from the core of the lava flow to the substrate. Large arrows represent movement of steam towards topographic highs. The dashed black line represents a potential ice table depth.

5.4 PROPERTIES OF THE SUBSTRATE (MFF)

The abundance of yardangs throughout the MFF suggests the unit is comprised of varying degrees of lithological competence (Ward, 1979; de Silva et al., 2010). Assuming a pyroclastic origin, this could be due to layering of indurated facies with more friable ash/pumice facies, with welding and jointing further influencing the lithological properties (de Silva et al., 2010). The MFF is also thought to be generally very fine grained (e.g., Christensen, 1986; Schultz & Lutz, 1988; Hynek et al., 2003) and a major source for redistributed aeolian material (Kerber & Head, 2011), as well as the pervasive global dust cover observed on Mars (Ojha et al., 2018). Ground penetrating radar sounding of the MFF (via the SHARAD instrument aboard the Mars Reconnaissance Orbiter and the MARSIS instrument aboard the Mars Express) report permittivity values consistent with low density material (~1.8 g/cm^3) that is either dry and extremely porous, or of some mixture of sediment and pure water ice (Watters et al., 2007; Carter et al., 2009; Ojha & Lewis, 2018); however, there is general agreement that high porosity is likely an intrinsic property of the MFF.

Lithological heterogeneities within a massive ignimbrite, due to zones of welding/compaction, fracturing, mineralogical alteration, etc., ultimately affect its hydrologic properties (Smyth & Sharp, 2006). Permeability and porosity are key parameters that control steam accumulation and transport, determining preferential sites for explosive steam eruptions and, thus, controlling the physical location of rootless cones in a lava field (Boreham et al., 2018. High porosity values should result in some degree of lateral steam transport, with vapor being drawn from deep in the substrate, and ideally towards topographic highs. Permeability, on the other hand, would affect the pore pressure during steam generation, with lower permeability substrates experiencing faster pore pressure increases (Boreham et al., 2018). Therefore, it is reasonable that the MFF could have facilitated lateral transport of steam through its porous, friable facies, and build-up of pore pressure under its indurated, welded facies. Additionally, Dundas & Keszthelyi (2013) made the case for a thin layer of desiccated soil (such as an MFF derived dust mantle) overlying ice-cemented ground that could inhibit mixing of lava and water while becoming pressurized to the point of explosive excavation.

CHAPTER 6

DISCUSSION

The presence of rootless cones in Cerberus Palus and the Aeolis Trough suggest that volatiles were present in the substrate at the time of the Athabasca flood lava eruptions (late in the Amazonian). At these latitudes (~0-10° N), ice would not have been stable in the subsurface at current or low obliquities. Their presence suggests one of three things: 1) the Athabasca flood lavas were emplaced during a period of high obliquity when ice was stable, at least ephemerally, in the substrate, 2) the water flood hypothesized to have preceded the Athabasca lavas was voluminous and extensive enough to saturate the substrate even at the furthest reaches of the subsequent lavas (including in the Aeolis Trough, prior to the breach of the dam), and the lavas arrived before it could be sublimated, or 3) the water in the substrate was originally stored in a more stable form (for example, as adsorbed water or hydrated minerals).

In the first and last case, evolution in our thinking of how rootless cones are formed is needed, because neither requires immediate intimate mixing of volatiles and lava in an Earth-like way (they require either time for the subsurface ice to melt or the water to be baked out of hydrated minerals). It has been calculated that much less water is required to build cones in explosive eruptions on Mars than on Earth; about seven times less water estimated by Keszthelyi et al. (2005) and about 4-16 times less by Greeley and Fagents (2002). While confined, dynamic mixing of lava and water is generally the favored model for terrestrial rootless cone formation, large volumes of surface water should not be necessary for explosive, cone building steam eruptions.

At the present obliquity (~25°), water ice is reported to be unstable between ±40° latitude (e.g., Mellon & Jakosky, 1993), however, modeling by Laskar et al. (2004) has shown that obliquities have ranged from ~25-45° over the past 20 Myr. Chamberlain & Boynton (2007) report that at high obliquities (>35°), high albedo and low thermal inertia surfaces in equatorial regions could allow for ice to remain stable at very shallow depths; the MFF deposits represent one such surface (Mellon & Jakosky, 1993). Bound water is also thought to represent a possible significant source of volatiles in Martian substrate, the release of which would act to raise gas pressures and increase the thermal conductivity of the regolith, accelerating heat transfer from overlying lava to the deeper substrate (Milliken et al., 2007).

There are many confounding elements regarding the nature and presence of the MFF. From a local perspective, I could conclude that its high porosity might allow it to soak up water from an Athabasca flood, or simply to serve as a convenient conduit for escaping steam. On the other hand, since the MFF is regionally associated with anomalously high hydrogen signatures (Feldman et al., 2004a; Wilson et al., 2018), it is possible that the increased volatile content is something intrinsic to the MFF itself, at least in Aeolis and Zephyria Plana, that still persists today (such as a high proportion of zeolites or other hydrated minerals). While the underlying topography and substrate composition of Cerberus Palus is largely unknown, rootless cones in the distal reaches of Cerberus Palus could have also involved heating of MFF substrate. The possibility of Athabasca flood lavas overwhelming outlying MFF outcrops, which have been found hundreds of kilometers north of its current boundaries (Harrison et al., 2010), cannot be ruled out.

Ultimately, the issue of the nature of the volatiles that interacted with the Athabasca flood lavas to create the rootless cones reported in question merits much further work. Modeling of the thermodynamic response of hydrated minerals and interpore adsorbates in phreatomagmatic processes, which there is a scarcity of, would help to constrain this problem. Calculations of the contribution of pressure and temperature by the Cerberus Palus lava lake at various stages of flow emplacement is also a necessary next step.

CHAPTER 7

CONCLUSIONS

Volcanic rootless cones throughout southern Cerberus Palus and the Aeolis Trough indicate the presence of near surface volatiles at the time of lava emplacement, perhaps $\leq$20 Ma. The form of these volatiles is unclear, with pore ice, bulk ice lenses, ephemerally stable liquid water, adsorbed water, and hydrous minerals all being possible to various degrees. Multiple mechanisms allowed for steam eruptions, resulting in landforms of varying scale and morphology:

- In southern Cerberus Palus, volcanic rootless cone formation was controlled by the ‘fill and spill’ style of lava emplacement. Steam eruptions were triggered by draining of the ponded lava, which led to depressurization of supercritical fluids in the substrate, allowing them to vaporize and excavate overlying lava to construct cratered cones.
- At the western margin of southern Cerberus Palus, ‘thin rimmed rings’ analogous to spatter rims formed due to steam escaping through the substrate, towards flow margins. Low energy bubble bursts through the thin lava created rings of competent spatter.
- Where the AVFL interacted with the MFF material surrounding southern Cerberus Palus, volcanic rootless cones preferentially formed atop lava draped meso-yardangs, implying a genetic relationship. The lithological properties likely allowed for lateral transport of steam towards the topographic peaks of the meso-yardang hulls, where steam became trapped and over pressurized until explosive excavation of the yardang occurred.
- The pitted terrain in the Aeolis Trough was created as a by-product of some mechanism similar to hydrothermal venting, where steam generated in the lava heated substrate escaped explosively through high stands of less consolidated MFF material, constructing rimmed pits of fragmented material.

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BIOGRAPHICAL SKETCH

Kaitlyn Stacey is a native of Dallas, Texas. After graduating from Plano East Senior High School, she attended The University of Texas at Dallas and received her Bachelor of Science with a major in geosciences in December 2016. In August 2016, she began her master's degree in geosciences at The University of Texas at Dallas. During the course of her graduate education, she worked as a teaching assistant and completed an internship at the NASA Jet Propulsion Laboratory.

CURRICULUM VITAE

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EDUCATION

The University of Texas at Dallas

M.S. in Geosciences under Dr. Robert Stern August 2016 – January 2019
Thesis: *Interactions between Athabasca Valles Flood Lavas and the Medusae Fossae Formation: Implications for Lava Emplacement Mechanisms and the Triggering of Steam Explosions*

B.S. in Geosciences August 2012- December 2016

JOB EXPERIENCE

- Student Worker, UTD Department of Biological Sciences, August 2017-present
- Graduate Student Intern, NASA Jet Propulsion Laboratory, May 2017-August 2017
- Teaching Assistant, UTD NS&M, “Our Nearest Neighbors in the Solar System,” January 2017-May 2017

LEADERSHIP

- Vice President of the UTD Women’s Rugby Club from May 2017- May 2018
- Served as UTD Geoclub President from 2014-2015 and Secretary from 2013-2014

ACADEMIC HONORS

- Dallas Geological Society Scholarship recipient in 2017
- UTD Geoscience department scholarship recipient in 2016
- Dean’s List at UT Dallas in 2013
- Admitted into the Delta Epsilon Iota honor society in 2013
- Outstanding Student Volunteer Award at the GSA South-Central meeting in 2013
- Academic Excellence Scholarship recipient at UT Dallas in 2012

RESEARCH EXPERIENCE

- Lunar Planetary Institute, Meteor Crater Field Camp, October 2018
- Lunar Planetary Institute, Short Course and Field School at the Sudbury Impact Structure, September 2017
- Jet Propulsion Laboratory Graduate Student Intern, June 2017- August 2017
- Selected for the 2017 Summer Internship Program at JPL to work with Dr. Laura Kerber. Research assignment involved geological mapping and annotation of the Medusae Fossae Formation on Mars using remote sensing techniques.
- UTD Research Assistant, May 2016-June 2016.

RA for the UTD Ellison Miles Foundation research group in Fish Lake Valley, Nevada. Assisted with structural geology research including stratigraphic logging, LiDAR, and fault slip measurements

CONFERENCE ABSTRACTS

- Stacey, K., Khuller, A.R., & Kerber, L. 2018. The Medusae Fossae Formation in SW Elysium Planitia, Mars As a Record of Recurring Hydrogeologic Activity. 49th Lunar and Planetary Science Conference, abstract #2815.
- Stacey, K. & Kerber L. 2017. Cratered Cones in Southern Cerberus Palus, Mars: Evidence for phreatovolcanism associated with interactions between Amazonian aged lavas and the Medusae Fossae Formation. AGU Fall Meeting, abstract # P33B-2879.

VOLUNTEER EXPERIENCE

- Student Volunteer for the UTD Geoclub from August 2012-present
- Volunteer for the non-profit hiking organization, Condor Trekkers, in Sucre, Bolivia during July 2016
- Volunteer at the Houston Museum of Natural Science from July 2015- December 2015
- Kitchen Volunteer at The Bridge homeless shelter from September 2013- December 2013

TECHNICAL SKILLS AND ABILITIES

- Experienced with geologic field mapping, using LiDAR scanners, and gravimeters
- Proficient in JMars, HiView, and ArcGIS programs
- Knowledgeable with usage of Scanning Electron Microscopes
- Conversant in Spanish

PROFESSIONAL ASSOCIATIONS

Student member of professional organizations: Geological Society of America, American Geophysical Union, Dallas Geological Society, and Delta Epsilon Iota.
Affiliated with SETI, NASA Jet Propulsion Lab, Condor Trekkers, The Planetary Society, UTD Women's Rugby Club, and UTD Geoclub

REFERENCES

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