Volcanism-induced, local wet-based glacial conditions recorded in the Late Amazonian Arsia Mons tropical mountain glacier deposits

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ABSTRACT
The tropical mountain glacial fan-shaped deposit (FSD) to the northwest of the Arsia Mons volcano on Mars contains numerous glacial and volcanic landforms. While most of the glacial landforms are interpreted to have formed by cold-based glacial processes, several glacial landforms near glaciovolcanic edifices are more consistent with localized wet-based glacial processes. These landforms include ribbed moraines, which suggest local, thermal transitions between wet- and cold-based ice; thrust-block moraines, whose formation is typically assisted by the presence of subglacial water; streamlined knobs that we interpret to have been sculpted by ice sliding along its base; and a braided outflow channel. The presence and association of these features, together with evidence of both subglacial volcanic eruptions and local ice-marginal advances, favor polythermal glaciers with localized wet-based conditions. We propose that lava-to-ice heat transfer during the eruption of the glaciovolcanic edifices caused the Arsia Mons paleoglacier to melt at its base in some areas, resulting in these locally wet-based glacial conditions. A polythermal glacier provides more potential microbial habitats and more connectivity between habitats than does a cold-based glacier, and we review glacial and glaciovolcanic habitats on Earth that may provide insight into the likelihood of potential microbial habitats within the Arsia Mons FSD on Mars.

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1. Introduction
To the west or northwest of each of the Tharsis Montes lie arcuate deposits, delineated by concentric ridges, known as the lobe- or fan-shaped deposits (e.g. Zimbelman and Edgett, 1992; Scott and Zimbelman, 1995). While the fan-shaped deposits (FSDs) were initially interpreted as having formed by either mass-wasting processes, volcanic processes, or tectonic deformation (see review in Shean et al., 2005), recent work (Head and Marchant, 2003; Shean et al., 2005, 2007; Forget et al., 2006; Kadish et al., 2008; Fastook et al., 2008; Scanlon et al., 2014) strongly supports the hypothesis (Williams, 1978; Lucchitta, 1981) that the FSDs are glacial in origin. Specifically, the morphology of landforms in the FSDs (Head and Marchant, 2003; Shean et al., 2005, 2007; Kadish et al., 2008; Scanlon et al., 2014) strongly resemble, and show the same spatial and stratigraphic relationships as, characteristic glacial landforms deposited from cold-based ice on Earth (e.g. Atkins, 2013). The term “cold-based” refers to glaciers whose basal ice temperatures are below the pressure melting point. Results from Mars global climate models show that ice should accumulate on the western flanks of the Tharsis Montes when martian spin-axis obliquity is high (Forget et al., 2006), and output from coupled ice-sheet models closely reproduce the footprints of the deposits (Fastook et al., 2008). Three geomorphologic facies comprise the majority of the deposit at Arsia Mons: a Ridged, Knobby, and Smooth Facies (Zimbelman and Edgett, 1992; Scott and Zimbelman, 1995), interpreted, respectively, as drop moraines, sublimation till, and remnant debris-covered glaciers (Head and Marchant, 2003).

Like the other Tharsis Montes FSDs (Shean et al., 2005; Kadish et al., 2008), the Arsia Mons fan-shaped deposit is associated with landforms that have been interpreted as subglacially erupted volcanic edifices (Fig. 1). These landforms, outlined in black in Fig. 1, include four plateaus interpreted as pillow mounds topped by hyaloclastite mounds; a flat-topped, steep-sided plateau interpreted as a tuya; a steep-sided ridge interpreted as an ice-confined lava flow; a series of digitate cliffs interpreted as ice-contact features; ridges grading into chains of pits, interpreted as eruptions spanning the boundary between permeable and impermeable ice; steep-sided, sunken-centered edifices interpreted as having formed by lava extrusions that chilled at the margins but whose still-molten centers receded into the vent; and numerous low,
steep-sided, areally extensive mounds interpreted as pillow mounds (Scanlon et al., 2014).

Amazonian-aged relict glacial deposits, including concentric crater fill, lobate debris aprons and lineated valley fill (e.g. Squyres, 1979; Squyres and Carr, 1986; Mangold, 2003; Milliken et al., 2003; Head et al., 2003; Garvin et al., 2006; Head et al., 2006, 2010; Dickson et al. 2008) are found from polar to equatorial regions of Mars. A lack of erosive features (e.g. grooves and molded forms) or evidence for associated fluvial activity, however, suggests that most of these deposits were formed by cold-based glaciers. In the Noachian and Hesperian eras, there is evidence that ice sheets at the south pole (e.g. Head and Pratt, 2001; Fastook et al., 2012), in Valles Marineris (e.g. Gourronc et al., 2014), in Argyre basin (e.g. Banks et al., 2009; Bernhardt et al., 2013), and in outflow channels (e.g. Lucchita et al., 1981) were wet-based, and that glaciolfluvial activity may have occurred in Gale crater in the Late Hesperian or more recently (Fairén et al., 2014), but as the martian climate became colder, cold-based glaciation became dominant. To our knowledge, outside of the Tharsis Montes FSDs, all conclusively Amazonian candidate polythermal or wet-based glacial deposits proposed thus far have been restricted to small regions within impact craters (Marchant et al., 2006; Hubbard et al., 2011), where basal melting may have been assisted by remnant thermal gradients after impact (Marchant et al., 2006).

On Earth, heat transfer from intrusive or extrusive volcanism underneath an otherwise cold-based ice sheet can be sufficient to allow melting and locally uncouple the glacier from the ground (e.g. Fahnestock et al., 2001; Fox Maule et al., 2005; Head and Wilson, 2007; Hambrey et al., 2008). On Mars, fluvial outflow channels and aligned, streamlined knobs that have been interpreted as drumlins in the Pavonis Mons fan-shaped deposit (Scott et al., 1998; Shean et al., 2007) suggest that volcano–ice interactions may have allowed local basal melting in the Pavonis tropical mountain glacier, though it is unclear whether the stratigraphic position of the streamlined knobs is consistent with the hypothesis that they are drumlins. No evidence for fluvial flow or wet-based glacial conditions has been documented, however, in the Olympus Mons glacial deposits or the Ascreaus Mons FSD (Milkovich et al., 2006; Kadish et al., 2008). In the Arsia Mons FSD, we find several characteristic classes of wet-based glacial landforms. The spatial relationships of these landforms to each other and to the documented glaciolvolcanic edifices in the deposit suggest that the Arresia glacier was locally wet-based (i.e., polythermal), with volcanism rather than climate causing the wet-based conditions.

2. Data

Using ArcMap 10.0, we constructed a ~5 m per pixel basemap of all Reconnaissance Orbiter (MRO) Context Camera (CTX) images (Malin et al., 2007) in the Arsia Mons fan-shaped deposit. Where CTX coverage was absent or unclear, we consulted High Resolution Stereo Camera (HRSC) images with 10–30 m per pixel resolution (Neukum and Jaumann, 2004). The glacial debris and atmospheric dust covering much of the Arresia FSD obscure fine-scale features and dominate spectroscopic data, respectively, limiting the usefulness of HiRISE and CRISM data in the vicinity of the landforms we describe here. We obtained topographic information from 128 pixel per degree (~463 m per pixel) resolution MOLA (Zuber et al., 1992; Smith et al., 1999) data and HRSC-derived Digital Elevation Maps (DEMs) with ~100 m per pixel resolution (Dumke et al., 2008). These data were processed using the Spatial Analyst toolkit in ArcMap 10.0.

Fig. 1. Geomorphological unit map of the Arresia Mons fan-shaped deposit (FSD), after Zimbelman and Edgett (1992) and Scott and Zimbelman (1995). Legend for color swaths is provided in figure. Elsewhere, thin red lines denote large volcanic grabens, white lines denote contacts between units (dashed where inferred), and black lines denote the outlines of glaciolvolcanic landforms and modified moraine ridges. Blue and white dots in the smooth facies denote pits and knobs, respectively. THEMIS 100 m/pixel daytime image mosaic; modified from Scanlon et al. (2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
3. Glacial landforms

3.1. Landform associations near the glaciovolcanic “Northwest Plateau”

A plateau towards the northwest of the Arsia Mons FSD (the “Northwest Plateau”), first described by Wilson and Head (2007a, 2007b) and later by Scanlon et al. (2014), is interpreted to have formed in a subglacial eruption (Fig. 2). The broad lower-elevation mass of the plateau is interpreted as an effusive pillow eruption. The steep, central mound superimposed upon it is interpreted in Scanlon et al. (2014) to have formed in a later, explosive phase of the eruption that began after subglacial meltwater drained from the edge of the glacier and the ice above the vent melted and thinned. Here we briefly review how this association of landforms, described in greater detail by Scanlon et al. (2014), exemplifies the interactions between glaciovolcanic activity and glacier thermal regime recorded in the Arsia Mons FSD.

3.1.1. Observations

Directly downslope of the plateau, and in the inferred direction of the paleo ice-surface slope, several shallow channels emerge from underneath mounds of glacial debris and coalesce into a braided channel ~35 km long and ~35 m deep where topographic data is available. Between the plateau and the glacio-fluvial channels lies a field of knobs that are elongated and streamlined in the downslope and inferred down-ice direction. Two sharp-crested ridges, grading downslope to broad-crested ridges in the inferred ice-flow direction, emerge from the steep upper mound of the plateau and superimpose the lower plateau. The long axes of the concentric ridges immediately downslope of the plateau are highly arcuate in the inferred down-ice direction compared to nearby members of the Ridged Facies. These ridges are superimposed non-destructively upon other ridges with similar morphology (Fig. 3), and are similar in size and shape to Ridged Facies members at the same radius from Arsia Mons.

3.1.2. Evidence of wet-based glacial activity

On the basis of their braided planform and their emergence from glacial debris, we have interpreted the braided channels downslope of the Northwest Plateau as fluvial channels, indicating the production and flow of a substantial volume of water at the base of the glacier (Scanlon et al., 2014). The streamlined planform and consistent northwest-to-southeast axis of elongation shared by the field of elongated knobs suggests formation by local glacial scour, possibly in a process analogous to the formation of terrestrial drumlins. On the basis of their morphology, size, and downslope transition from sharp-crested to broad-crested (consistent with the expected behavior of subglacial channels with increasing distance from a heat source; e.g. Shreve, 1985), Scanlon et al. (2014) interpreted the sinuous ridges as accumulations of glacio-fluvial debris (i.e. eskers), which are characteristic of wet-based glacial environments. The non-destructive superimposition of the arcuate ridges downslope of the plateau upon underlying features and their morphological similarities to members of the Ridged Facies suggest that the arcuate ridges, like the Ridged Facies ridges (Head and Marchant, 2003), are drop moraines. The tighter radius of curvature shown by the ridges downslope of the plateau, relative to nearby members of the Ridged Facies, suggests that they were formed at the edges of a lobe of ice elongated in the same direction implied by the other 3 landform classes, consistent with a local increase in longitudinal ice-flow velocity and local ice-margin advance (Fig. 4).

3.2. Ridges transverse to inferred glacial flow

The Lobate Facies (Zimbelman and Edgett, 1992; Fig. 1) is a unit in the Arsia Mons FSD characterized by numerous, densely distributed steep-sided, lobate scarps and ridges, some of which grade upscale into chains of pit craters. The steep-sided features are interpreted as subglacial lava flows, and the pit craters as the sites of phreatomagmatic eruptions under thinner ice, suggesting that volcano–ice interactions were common in this region of the FSD (Scanlon et al., 2014).

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Fig. 2. The Northwest Plateau: (a) CTX image mosaic. (b) Sketch map. The Ridged Facies is shaded in red and the Knobby Facies is shaded in blue. Fluvial channels are denoted by light blue lines and streamlined knobs are denoted by green lines. Boxed insets show the locations of Figs. 3 and 7. Modified from Scanlon et al. (2014). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
3.2.1. Observations

At the contact between the Lobate and Knobby Facies (Fig. 5) lies a ~17 km wide field of sharply defined, commonly asymmetric, regularly spaced, concentric or anastomosing ridges. The ridges are oriented transverse to inferred ice-flow directions, and are up to 30 km long and typically 500 m to 1 km wide (Fig. 6). Where HRSC DEM coverage is available, the ridges are typically 10–50 m high.

Smaller ridges (~200 m wide and not high enough to be resolved by the HRSC DEM), of similar shape and similar spacing relative to their size, occur superimposed upon the Northwest Plateau (Section 3.1; Fig. 7). The orientation of these ridges, southwest-to-northeast, is also transverse to the direction of inferred glacial flow based on local topographic slopes and the landforms described in Section 3.1.

3.2.2. Evidence of wet-based glacial activity

On the basis of their asymmetric and sharp-crested morphology, their concentric or branching arrangement, their regular size and spacing, their orientation transverse to inferred ice-flow directions, the fact that they do not appear to gently drape underlying topography as do the drop moraines in the Ridged Facies (Head and Marchant, 2003; Shean et al., 2007), we interpret both the transverse ridges between the Lobate and Knobby Facies and the transverse ridges superimposed on the Northwest Plateau as ribbed moraines formed in association with glacier ice that locally achieved wet-based conditions (cf. Dunlop and Clark, 2006).

Ribbed moraines are unusual and complex glacial landforms. They do not form alongside ice margins, but rather are produced locally at the base of polythermal glaciers (e.g. Dunlop and Clark, 2006 and sources therein; Möller, 2006). The precise mechanism by which they form is incompletely understood, but candidate origins include those in which (1) the moraines are the remnants of a frozen till sheet that extends and fractures when a wet-based, downslope region of a glacier flows more rapidly than a cold-based interior region (Hättestrand and Kleman, 1999); (2) ice-cored moraines left by a cold-based glacier are re-sculpted into ribbed moraines when subsequently overrun by wet-based ice (Möller, 2006, 2010); (3) the crests of the moraines represent the crests of former waves produced by a fluid dynamical instability in the flow of glacial ice and subglacial till (Dunlop et al., 2008; Fowler, 2009; Chapwanya et al., 2011); or (4) moraines form when seasonal or climatic variations in subglacial meltwater content cause the glacier bed to transition locally from an extensional to a compressional deformation regime (Lindén et al., 2008; Stokes et al., 2008). Whether all subtypes of ribbed moraine form by the same process is debated (e.g. Hättestrand and Kleman, 1999; Finlayson and Bradwell, 2008; Lindén et al., 2008; Chapwanya et al., 2011), but most researchers acknowledge that marked changes in horizontal ice-flow velocity, most easily accomplished beneath polythermal glaciers, are a crucial factor in their formation (Finlayson and Bradwell, 2008).

We propose that the heat produced during episodes of extrusive subglacial volcanism in the Lobate Facies led to basal meltwater production, resulting in spatial and temporal gradients in basal sliding and longitudinal ice-flow velocity (Fig. 8). These conditions would have led to the development of the population of large transverse ridges at the contact between the Lobate and Knobby Facies by one of the formation mechanisms for ribbed moraines discussed above.

We assert that the volcanic construction and subsequent cooling of the Northwest Plateau affected the thermal regime of adjacent glacier ice, producing polythermal conditions that led to the development of the population of small ribbed moraines atop the plateau. The superposition of ridges on top of the plateau suggests an origin via temporal, as well as spatial, transitions between wet-based and cold-based ice conditions. Specifically, the ice directly above the Northwest Plateau would have remained wet-based longer than the ice farther downslope from the volcanic heat.

Fig. 3. Close view of drop moraines downslope of the Northwest Plateau. Drop moraines reflecting locally enhanced glacial flow (in the direction indicated by cyan arrow) are non-erosively superimposed (red arrows) upon earlier drop moraines concentric with the boundaries of the Ridged Facies. CTX image P19_008605_1772_X1_025129 W. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
source, causing compressive stress and ribbed moraine formation above the plateau.

3.3. Enlarged, ridged moraine

At the northern edge of the FSD (Figs. 1 and 9) lies an L-shaped ridge ~50 km long, up to ~450 m high, and up to ~4 km wide. Due to its height, steep sides, and the channeled morphology at its distal end, this ridge is interpreted to have formed as an ice-confined volcanic flow; heat transfer from this volcanic flow to the surrounding ice is conservatively estimated to have generated ~38 km³ of liquid water (Scanlon et al., 2014). Further upslope of this ridge lies the glaciovolcanic Lobate Facies (Fig. 5). The morphology of the outermost moraine of the FSD in this region suggests that the subglacial volcanism that formed the L-shaped ridge and/or the Lobate Facies caused wet-based behavior in this part of the paleoglacier.

3.3.1. Observations

Downslope and to the west of the ridge (Fig. 9), the terminal moraine of the FSD differs dramatically in size and appearance from elsewhere in the deposit (Fig. 10). The moraine is up to 3 km wide here, whereas it is typically only a few hundred meters wide, and is taller here (up to ~125 m) than elsewhere in the deposit (Fig. 11). The moraine has several small parallel ridges at its top and its MOLA profile resolves one broad ridge superimposed on the moraine.

3.3.2. Evidence of wet-based glacial activity

Based on its size, surface appearance, and topographic profile, as well as its exclusive occurrence downslope of the region of the FSD containing the largest glaciovolcanic edifice and the highest density of glaciovolcanic landforms, we interpret this feature as a thrust-block moraine (also known as a composite moraine, or sometimes as a push moraine; e.g. Benn and Evans, 2010). The

Fig. 4. Map view of volcanic eruption (bright orange/gray) under ice sheet (white) on flank of volcano (dark brown), and resulting moraines (light brown lines): (a and b) Local eruption generates heat and initiates ice acceleration and ice-margin advance. (c) As volcanism wanes, basal ice cools below the pressure melting point and subglacial materials may be entrained; the entrained debris, as well as any previously deposited supraglacial debris, eventually falls passively at stationary ice margins, producing drop moraines. (d and e) As the glacier recedes, drop moraines left behind will continue to delineate local still stands in overall ice recession. Based on variable ice margin geometry, these superposed moraines may cross-cut, at oblique angles, drop moraines deposited during earlier times (Fig. 3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 5. Regional context map showing contacts between the Lobate, Ridged, and Knobby facies. The area shown in Fig. 6 is highlighted by a white box.

Fig. 6. Concentric, sharp, evenly spaced ridges, interpreted as ribbed moraines, at the contact between the Lobate Facies and the Knobby Facies (location indicated by white box in Fig. 5). CTX image mosaic.
multi-ridged appearance (Fig. 10) and profile (Fig. 11a and b) of the moraine is consistent with an imbricate stack of thrust slabs. On Earth, such thrust-block moraines form where high longitudinal stresses act on weak subglacial sediments or bedrock, e.g. adjacent to a steeply sloping ice margin or across a thermal boundary between wet-based and cold-based ice conditions. Basal debris, entrained by regelation, may be advected upward along thrust planes in the ice, potentially producing an imbricated moraine ridge. Locally, elevated pore pressures that arise from permafrost-confined aquifers beneath polythermal glaciers may enhance basal deformation and entrainment (e.g. Boulton et al., 1999; Bennett, 2001; Benn and Evans, 2010), leading to the formation of thrust-block moraines. In addition to being influenced by rheological properties of the deforming substrate, the size of thrust-block moraines scale with the magnitude and rate of glacial advance (Bennett, 2001). Within purely cold-based glaciers, thrust-block moraines have only been documented where ice advances into marginal lakes, where wet lacustrine sediment may freeze onto basal ice and move upward along local thrust planes (Fitzsimons, 2003; Hambrey and Fitzsimons, 2010); this process, however, is unlikely to have been the case at Arsia Mons. Instead, we propose that the large moraine ridge in the Arsia Mons FSD reflects polythermal thermal variation near the ice margin. Local, wet-based conditions associated with periods of subglacial volcanism were likely associated with basal entrainment and increased sediment transport downglacier (Section 3.3), which form directly over regions postulated to experience transitions from wet-based to cold-based glacier ice.

4. Discussion

Four characteristic classes of wet-based or polythermal glacial landforms are observed near glaciovolcanic edifices in the Arsia Mons FSD: (1) outflow channels, which record the release of large...
volumes of meltwater; (2) streamlined knobs, which record the direction of glacial motion as well as its erosive power; (3) ribbed moraines, which are thought to indicate transitions between wet-based and cold-based glacier ice; and (4) a large thrust-block moraine, which records the local deformation of basal sediment by large glaciotectonic stresses typically associated with either fast-flowing glacier ice (surging) or transitions from wet-based to cold-based glacier ice. Together, the landforms provide a coherent history at each glaciovolcanic site (Fig. 13): uniform ice-flow directions are recorded both by the streamlined knobs and the ribbed
moraines at the Northwest Plateau. Furthermore, the outflow channels emerge directly beyond these landform, as would be expected if the enhanced flow was stimulated by wet-based conditions. Similarly, the ribbed moraines downslope of the numerous glaciovolcanic edifices in the Lobate Facies and the thrust-block moraine farther downslope at the terminus of the deposit both point to a transition from wet-based to cold-based ice, which is consistent with the placement of glaciovolcanic landforms in the FSD (Fig. 13). These consistent landform associations imply that glaciovolcanic activity was sufficient to alter the local thermal regime of the Arisia Mons tropical mountain glacier, and their exclusive association with glaciovolcanic edifices implies that climate and pressure effects were never by themselves sufficient to cause basal melting in the glacier.

5. Potential microbial habitats in the Arisia Mons FSD

On Earth, glaciovolcanic environments provide a range of microbial habitats (e.g. Cousins and Crawford, 2011). While the chemical conditions would have differed from those in terrestrial glaciers due to the lack of an oxygen atmosphere and a vigorous biosphere, plausible redox couples and nutrient sources could have made wet glacial environments on Mars hospitable to life (Cockell et al., 2011). Since such environments would have originated from volcano–ice interaction in the case of this deposit, volcanic gases in some of the habitats would have further strengthened redox gradients and provided an additional carbon source in the form of volcanic CO₂ (Skidmore, 2011). The Amazonian aqueous environments induced by glaciovolcanism may have been shorter-lived than those arising due to impact heat in large craters (e.g. Abramov and Kring, 2005; Barnhart et al., 2010). Taking the ~10² m³s⁻¹ effusion rates estimated for flows at Ascræus Mons (Hiesinger et al., 2007) as plausible rates for flows in the Arisia Mons FSD, the volumes of FSD landforms like the Northwest Plateau and L-shaped ridge (on the order of 10¹⁰ m³; Scanlon et al., 2014) suggest a duration of years to tens of years for edifice construction and therefore at least that duration for wet-based conditions. Englacial water bodies formed in response to these eruptions, however, would likely have persisted for hundreds to thousands of years before freezing (Scanlon et al., 2014).

The following environments, which geomorphological evidence indicates were present in the Arisia Mons FSD paleoglacier, are inhabited on Earth.

5.1. Englacial and basal lakes

The glaciovolcanic landforms in the Arisia Mons FSD are likely to have generated several englacial lakes with volumes on the order of tens of cubic kilometers and longevity of hundreds to thousands of years (Scanlon et al., 2014). The few terrestrial volcanically generated englacial lakes whose ecosystems have been surveyed (Gaidos et al., 2004, 2008; Marteinsson et al., 2013) contained microbial communities capable of fixing carbon and nitrogen, and including organisms related to known acetogens, sulfate reducers and iron reducers. These communities are supported by sediments and bottom waters rich in volcanic CO₂, H₂, ferric iron, and sulfur compounds, as well as oxygen from the melted glacial ice (Jóhannesson et al., 2007; Marteinsson et al., 2013).

At least one basal lake beneath 800 m thick ice in the Antarctic Ice Sheet has been shown to host a microbial community supported by chemooautotrophic production (Christner et al., 2014). Since the Arisia Mons paleoglacier experienced transient wet-based conditions, analogous basal lakes within the FSD may have provided additional habitats for microbial life. Other ice-covered lakes, such as those in the Antarctic Dry Valleys (e.g. Roberts et al., 2000; Murray et al., 2012), are poorer analogs to the Arisia Mons lakes because they originated as subaerial lakes. Subaerial lakes can be colonized more easily than englacial lakes due to their exposure to surface runoff and dormant, windborne microorganisms, and after they develop an ice cover their productivity can still be boosted by legacy carbon from the earlier lake ecosystem and other nearby environments (Priscu et al., 1999).

Phylogenetic evidence suggests that the microbes that colonize terrestrial subglacial volcanic lakes originate in a variety of other environments, including glacial ice and snow, dust and marine aerosols that work their way into the lakes long after being deposited on the glacier surface, drainage of surface meltwater into the lake (Gaidos et al., 2004), or subsurface aquifers in contact with the subglacial melt (Marteinsson et al., 2013). Neither surface runoff nor iced-over subaerial lakes are likely to have been present near the subglacial lakes in the Arisia Mons FSD. The dike intrusions in the Arisia Mons FSD could potentially have warmed the subsurface enough and melted enough ground ice for a liquid aquifer to persist (e.g. Head and Wilson, 2002). Such an aquifer could have hydrologically connected some habitats within the deposit, enabling microorganisms to move between them. However, due to the regional dust cover mantling the deposits, no spectral...
evidence for hydrothermal alteration minerals has yet been found in the deposit, and any fine-scale morphologic features of hydrothermal systems would have been obscured by glacial debris in the Ridged, Knobby and Smooth Facies. If circulating hydrothermal fluid was not present, putative martian life could still have colonized the lakes if airborne propagules (perhaps the long-dormant...
inhabitants of another transient surface habitat) worked their way into the glacial ice, or if the ice itself was inhabited or contained dormant life forms.

5.2. Wet-based glacier ice

While the Arsia Mons glacier was cold-based through much of its spatial and temporal extent (Head and Marchant, 2003), we have shown that subglacial eruptions induced local wet-based conditions in several regions of the Arsia Mons paleoglacier. Microbial communities have been observed directly (e.g. by microscopy or metagenomic analyses) or indirectly (e.g. by isotopic measurements) in the basal ice, water, brines, and sediments of wet-based and polythermal glaciers in Alaska, Antarctica, Canada, Greenland, New Zealand, and Norway (see review in Hodson et al., 2008). In some cases these communities are more diverse than the surface glacier communities (Hamilton et al., 2013). The environment appears to support organisms that participate in iron and sulfur cycling (Mikucki et al., 2004, 2009), methanogenesis (Stibal et al., 2012a), and other processes that could have been viable on Mars. Wet subglacial sediments in the Arsia Mons glacier could have been inoculated by the same sources as subglacial lakes; groundwater connections, organisms in the ice, or organisms in surficial or englacial debris.

5.3. Glacial ice and debris

The ubiquity of the Knobby Facies, which forms from the sublimation of debris-rich ice (Head and Marchant, 2003), indicates that much of the Arsia Mons glacier was rich in debris. In terrestrial glaciers, debris-rich ice contains more microorganisms than clean ice because the debris is a source of nutrients and electron donors or acceptors. Furthermore, thin films of liquid water are present at mineral–ice interfaces at temperatures well below freezing (Wetlaufer, 1999; Price, 2007). Even when these films are too small for microbes to move freely, dissolved ions and organic compounds are still mobile and allow microbes to carry out metabolic processes including methanogenesis, denitrification, sulfate reduction, and iron reduction (see review in Price, 2007).

Clean ice can also contain habitable microenvironments at subfreezing temperatures. Small amounts of impurities (including nutrients and organic compounds) have been shown to segregate into veins between grains of ice due to their low solubility in solid ice. These veins contain concentrated nutrients and are large enough to allow microbes to move within them, and are thought (Price, 2000) to be the reason viable microbes have often been isolated from ice cores (e.g. Christner et al., 2000). Organisms adapted to subfreezing temperatures can survive, perhaps indefinitely (Price, 2000), and even grow in these veins (Mader et al., 2006; Dani et al., 2012).

While such environments are unlikely to be as productive as macroscopic englacial water bodies, they may have represented refugia from which these larger bodies could be colonized. Remnant ice in the deposit (Head and Marchant, 2003; Shean et al., 2007; Scanlon et al., in review), could provide these habitats even today. Hollowed ridges at the western edge of the deposit (Scanlon et al., in review), which have been interpreted to represent former snow dunes, indicate that snow or ice was transported and reworked by wind in the region surrounding the deposit. This would have helped disperse any ice-dwelling organisms, increasing the potential for colonization of any glacial or glaciovolcanic habitats in the region.

5.4. Hyaloclastite and palagonite

While the subglacially erupted edifices in the deposit have not yet been imaged with resolution high enough to identify surface textures, and the material mantling the deposit may prevent confident identification even then, these structures should all contain abundant basaltic glass due to the rapid chilling of basaltic lava against ice as it erupted. We have argued (Scanlon et al., 2014) that many of the landforms within the FSD should have glassy surfaces, and that several should consist largely of rapidly quenched basaltic tephra. Compared to crystalline basalt, hyaloclastite is a favorable habitat for microbial life (as is its alteration product, palagonite) because the lack of crystal structure makes nutrients in the rock more easily accessible (Cockell et al., 2009). These basaltic glasses are inhabited in exposed flows that were erupted subglacially, in submarine lavas, and in subglacial lakes (e.g. Cockell et al., 2009; Gaidos et al., 2004; Thorseth et al., 2001, respectively), and are among the environments in which putative evidence of early terrestrial life has been found (Banerjee et al., 2006). The range of autotrophic metabolisms supported by the volcanic glass environment on Earth remains incompletely characterized, however (Cockell, 2011).

5.5. Biosignature preservation potential

In environments well-suited to the preservation of molecular and morphological biosignatures, biogenic material is concentrated by physical processes, protected by rapid burial from oxidation and ultraviolet radiation at the surface, and isolated from aqueous or thermal alteration after burial; ideally, phyllosilicates are deposited simultaneously, aiding in preservation (Summons et al., 2011). While spectrometers have thus far been unable to conclusively determine the mineralogy of the region, several landforms in the deposit meet the other criteria.

The Northwest Plateau is one example of a location within the FSD where biosignatures may have been generated and preserved.
In terrestrial subglacial volcanic lakes, microbes are concentrated in the hyaloclastite bottom sediments rather than in the water column (Gaidos et al., 2004). Any microorganisms inhabiting the englacial lake above the Northwest Plateau would almost certainly have been concentrated in the hyaloclastite for the same reasons. Some of these sediments currently comprise the eskers extending from the tephra mound; the top few meters of sediment in the larger esker would have easily been able to protect biogenic material deeper in the esker against ionizing radiation (Kminek and Bada, 2006). The rest of the sediments are similarly protected by meters of Knobby Facies material.

In addition to promoting redox gradients that support life, the hydrothermal circulations present during the construction of subglacial edifices like the northwest plateau also promote the formation of sulfates and other minerals that can preserve chemical and morphologic biosignatures (Cousins et al., 2013). Furthermore, the knobby material itself is former englacial debris; as the Arsia Mons glacier sublimed, any organic material that froze out of the water column in the lake would ultimately be concentrated in the Knobby Facies, along with material from habitats that may have existed in the Arsia Mons glacier but are too small to detect by remote sensing, such as the sub-meter-scale “cryoconite holes” melted into ice where low-albedo supraglacial debris aggregates (e.g. Stibal et al., 2012b). There is no evidence to suggest that the eskers, the central mound of the plateau, or the Knobby Facies have been fluvially or thermally altered since their formation, except possibly by the deposition of volcanic ash.

6. Conclusions

Glaciovolcanic landforms are abundant in the Arsia Mons fan-shaped deposit. Previous work has made a strong case for cold-based glaciation at the Tharsis Montes, but new, higher-resolution data show that landforms indicative of local wet-based/polythermal conditions, include thrust-block moraines, ribbed moraines, highly arcuate drop moraines, streamlined knobs, and fluvial outflow channels. Since these landforms all occur exclusively in association with glaciovolcanic features, we conclude that the Arsia Mons FSD was left by a glacier whose local wet-based conditions were induced by volcanic warming rather than by climate.

The aqueous environments evidenced by the Arsia Mons FSD are exceptional in that they are comparable in size to similar Noachian-Hesperian environments, and potentially much longer-lived than other Amazonian environments. Furthermore, the Arsia Mons glaciovolcanic environments occurred recently enough (Kadish et al., 2014) that unambiguous molecular biomarkers have been retrieved from much older terrestrial environments (e.g. Brocks et al., 1999). If Mars Science Laboratory (Grotzinger et al., 2012) or other upcoming missions discover evidence for fossil or extant surface life on Mars, the Arsia Mons Fan-Shaped Deposit would be a well-suited target for future human or robotic exploration to determine whether it persisted into the modern era.

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