Cold-based mountain glaciers on Mars: Western Arsia Mons

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ABSTRACT
Surface environmental conditions on Mars are currently extremely cold and hyperarid, most equivalent to polar deserts on Earth. Coupling newly acquired Mars data with field-based observations regarding the flow, surface morphology, and depositional history of polar glaciers in Antarctica, we show that the multiple facies of an extensive fan-shaped deposit on the western flanks of Arsia Mons volcano are consistent with deposition from cold-based mountain glaciers. An outer ridged facies that consists of multiple laterally extensive, arcuate and parallel ridges, resting without disturbance on both well-preserved lava flows and an impact crater, is interpreted as drop moraines formed at the margin of an ablat ing and predominantly receding cold-based glacier. A knobby facies that consists of equidimensional knobs, each to several kilometers in diameter, is inward of the ridges; this facies is interpreted as a sublimation till derived from in situ downwasting of ash-rich glacier ice. A third facies comprising distinctive convex-outward lobes with concentric parallel ridges and aspect ratios elongated downslope likely represents rock-glacier deposits, some of which may still be underlain by a core of glacier ice. Taken together, these surficial deposits show that the western flank of Arsia Mons was occupied by an extensive mountain glacial system accumulating on, and emerging from, the upper slopes of the volcano and spreading downslope to form a piedmont-like fan.

Keywords: Mars, cold-based glaciers, rock glaciers, drop moraines, ablation till, Arsia Mons.

INTRODUCTION
Arsia Mons is one of the three Tharsis Montes shield volcanoes that cap the broad Tharsis Rise, a huge center of volcanism and tectonism spanning almost the entire history of Mars. Each of the Tharsis Montes, although largely constructed of effusive and explosive volcanic deposits, contains a distinctive and unusual fan-shaped deposit on their western flanks. These deposits, as exemplified by those on Arsia Mons (e.g., Zimbelman and Edgett, 1992; Scott and Zimbelman, 1995), usually contain three facies (Figs. 1A, 2A, 2B, 2C). (1) An outermost ridged facies (Fig. 2A) consists of a broad, thin sheet characterized by numerous ridges, tens of kilometers in length and spaced a few hundred meters to several kilometers apart, that pass across topographic barriers without obvious deflection. (2) A knobby-terrain facies (Fig. 2B) forms an extensive area of chaotic terrain that is characterized by subrounded several-kilometer-diameter hills; some hills form chains that are parallel to subparallel to the ridges in the ridged facies. (3) A smooth facies (Fig. 2C) contains arcuate lineations and diffuse to lobate margins; the smooth facies appears to overlie areas of the knobby facies. Scott and Zimbelman (1995, and references therein) described various hypotheses for the origin of these features, including one or more of the following: lahars, debris avalanches, landslides, pyroclastic flows, and/or causes generally related to the advance and retreat of ice (e.g., Lucchitta, 1981).

Two new developments are the basis for the research reported in this analysis. First, new Mars Orbiter Laser Altimeter (MOLA) altimetry and Mars Orbiter Camera (MOC) images from the Mars Global Surveyor mission have permitted us to characterize the fan-shaped deposit on Arsia Mons and its relationship to the rest of the volcano in much more detail. Second, ongoing research on polar glaciers in Antarctica has resulted in depositional models...
that are of sufficient detail to provide a framework for investigating glacier ice on Mars (Marchant et al., 2002; Denton and Marchant, 2000; Sugden et al., 1995). On the basis of present surface temperatures on Mars and those of the recent past, any mountain glaciers on Arsia Mons and nearby volcanoes were likely to be cold based and most similar to the slow-moving, cold-based glaciers of the Dry Valleys region of Antarctica (Schafer et al., 2000; Cuffey et al., 2000; Marchant et al., 2002; Atkins et al., 2002).

DESCRIPTION AND INTERPRETATION

Collectively, the Arsia Mons fan-shaped deposits (Fig. 1A) are ~350–450 km wide and extend ~500 km down the western flanks in a N55°W direction. They cover an area of ~180,000 km², about the size of the state of Washington, United States, or almost twice the size of Iceland. Mars Global Surveyor (MGS) MOLA data show that the summit of Arsia Mons is at ~17.76 km above the aeroid, rising ~16.8 km above the cratered terrain. The base of the most distal facies of the fan-shaped deposit (the ridged facies) is at ~2600 m elevation, ~15 km below the summit. The majority of the deposits are at elevations between 2600 m and 7000 m. They are late Amazonian in age and are largely contemporaneous with the latter phases of volcanism on Arsia Mons (interdigitate relationships with Tharsis Montes Formation Member 5 of Scott and Zimbelman, 1995, and possibly predating or being partly contemporaneous with Member 6).

Ridged Facies

The ridged facies consists of a series of >100 concentric ridges that extend several hundred kilometers beyond the break in slope at the base of Arsia Mons (Figs. 1A and 2A). Ridges are typically spaced ~1 km apart, and MOLA data show that individual ridges vary in height: the outer prominent ridge reaches heights of ~50 m, whereas typical inner ridges are 5–20 m high. MOC images show evidence for abundant dunes on and near the ridges, suggesting that the ridges are composed of fine-grained material that is subject to eolian modification. MOC images also show that the outermost ridge is asymmetrical; its steep side faces outward. Morphology of the smaller ridges varies, ranging from peaked, to rounded, to flat topped. We found no depositional or erosional evidence that might be associated with wet-based glaciers, such as eskers, sinuous channels, lake deposits, and/or braided streams; likewise, we found no evidence for ridge offsets that might represent tear faults resulting from uneven compression associated with landslide deposits, as seen in the Olympus Mons aureole (e.g., Francis and Waadge, 1983).

One of the most distinctive characteristics of the ridged facies is its superposition on a subjacent impact crater and lava flows without apparent modification (Williams, 1978; Lucchitta, 1981; Zimbelman and Edgett, 1992; Anguita and Moreno, 1992; Scott and Zimbelman, 1995; Helgason, 1999; Figs. 1A and 2A). We used detrended MOLA data to examine the local topographic relationships (Fig. 1B) and found that the lava flows emerging from the edge of the fan-shaped deposit could be readily traced inward beneath the ridged facies and even into the area beneath the knobby facies, apparently without major disruption and modification. The very distinctive substrate preserved below the ridges (both a crater, Fig. 2A, and an earlier phase of lava flows, Fig. 1A), the blanket-like nature of the ridged facies, and the extreme regularity of the ridges contrast distinctly with landslide-like features seen on the nearby Olympus Mons aureole (Francis and Waadge, 1983). Similarly, although dunes and ridges can be produced during pyroclastic flow emplacement, the regularity of the ridges and their great lateral ex-
tent would require an unexpected homogeneity in a turbulent flow. This distinctive and delicate relationship with underlying terrain suggests that the fan-shaped deposit was emplaced by a process that involved little interaction with the substrate. Consequently, we do not favor the hypothesis that the ridged facies represents the distal part of landslide deposits, and instead support Lucchitta (1981) and subsequent workers, and explore more specific glacial environments in which such features might form without modification of the substrate.

Terrestrial analogues for deposits on Arisia Mons occur in the Dry Valleys region of Antarctica. The Dry Valleys of southern Victoria Land (77°30’S, 162°E) occupy a hyperarid, cold-polar desert. Mean annual temperatures vary from −35 to 2°C in interior regions to −14°C near the coast. Thus, glaciers in this environment are polar cold based (the temperature throughout the glacier is below the pressure melting point, and deformation and movement occur within the ice), in contrast to temperate glaciers (the temperature at the movement occur within the ice), in contrast to temperate based (the temperature at the base is at the pressure melting point, and significant slip and erosion takes place at the base). Recent empirical and theoretical studies show that rates of subglacial erosion beneath cold-based glaciers in the Dry Valleys (Mouille Glacier) are as low as 9 x 10⁻⁷ to 3 x 10⁻⁶ m/yr (Cuffey et al., 2000) and that deposits from such glaciers (Atkins et al., 2002) pass undisturbed across lava flows, cinder cones (Wilch et al., 1993), and unconsolidated ash-avalanche deposits (Marchant et al., 1993, 1994; Fig. 2D). In interior regions of the Dry Valleys, glacier ablation is almost entirely by sublimation (>90%), and geomorphic traces of meltwater erosion are lacking (Marchant and Denton, 1996). Debris that falls onto mountain glaciers in this region is transported supraglacially (or englacially if debris falls in the accumulation zone) and is dropped passively at stationary ice margins to form drop moraines (e.g., boulder-belt moraines of Denton et al., 1993) (Fig. 2D). If ice-margin retreat greatly exceeds the delivery of debris to the glacier snout, then a thin drift sheet composed of isolated and perched clasts marks ice recession. Drop moraines and thin drifts deposited from advance and retreat of cold-based ice in the western Dry Valleys region are superposed with virtually no modification of the substrate (Marchant et al., 1994).

We thus interpret the ridged facies on Arisia Mons as a series of drop moraines, each representing a period of standstill of a cold-based glacier followed by a phase of retreat. The extremely even distribution of the ridges and their continuity mean that the debris distribution must have been extremely homogeneous and that the ice-front retreat must have been very even and symmetrical. The evenness of debris distribution favors widespread fine debris emplaced by pyroclastic eruptions or dust deposited from the atmosphere, as opposed to debris scoured from below the glacier (very unlikely, owing to preservation of underlying impact craters and lava flows) or deposited locally on top of the glacier by rockfalls or landslides.

**Knobby-Terrain Facies**

The next innermost facies of the fan-shaped deposit is composed of a largely chaotic assemblage of hills, some as much as several kilometers across, that are subrounded to elongated downslope; some hills are aligned and form arcs that in general are parallel to ridges in the distal facies. Viking images reveal a narrow transitional zone of >100 km between the outer ridged facies and inner knobby facies where both arcuate ridges and knobby terrain are interspersed. The deposits that constitute the knobby terrain are very homogeneous in local areas (e.g., Fig. 2B) and show little detailed structure as a whole. There is no evidence for banking or pile-up of the deposits behind the small number of underlying prominences. The relationship between the knobby facies and the underlying deposits is made clear by examination of detrended MOLA topography (Fig. 1B). Here, the distinctive underlying lava flows can be traced into the area of the ridged facies and then farther into the area of the knobby facies. The margins of the underlying flows have not lost their coherence, as they probably would if the knobby facies represented a landslide deposit. Instead, it appears as if the knobby facies has been deposited on top of the underlying lava flows without marked interaction with the substrate. Analysis of the interior of the knobby facies and the regions around its exterior reveals little evidence for features that might indicate melting, such as channels, ponded material, or eskers. MOC images show abundant evidence for eolian modification of the knobs and mounds.

On the basis of morphologic comparisons of the knobby facies with cold-based, debris-covered glaciers in the Dry Valleys region of Antarctica (Fig. 2E) (Sugden et al., 1995; Marchant et al., 2002), as well as the mapped distribution of the knobby facies inward of the ridged facies, we conclude that the knobby facies represents a sublimation till, likely produced by sublimation of debris-rich ice. Sublimation tills are similar to melt-out tills, but the ice is lost by sublimation, rather than by melting. Sublimation till formation requires contact of the ice with the atmosphere at the surface or through diffusion through pores, and the sublimation process can be very slow and nondisruptive, operating almost as a “deflation” and internal settling of the deposit as the ice is progressively removed. The process can also result in the remaining deposit being extremely loosely packed or friable (Lundqvist, 1989) and settling with time (Marchant et al., 2002). Grain size and particle characteristics will be inherited from the interstitial material in the parent ice deposits. Sublimation tills on top of glacial ice in Antarctica can reach thicknesses and porosities that insulate underlying ice from further diffusion and sublimation. Thus, in some cases, glacier ice that is older than 8 Ma has been shown to underlie sublimation till in the Dry Valleys (Sugden et al., 1995; Schaefer et al., 2000; Marchant et al., 2002).

Scott and Zimbelman (1995) interpreted the knobby facies as having formed in a wastage zone of an ice sheet and to include landslide material. In their assessment, a major bedrock scarp at the head of the knobby facies was interpreted as a detachment surface, part of the knobby facies representing supraglacial material derived from mass wasting and landslides. Thus, a major outstanding question in their interpretation is the relative significance of mass wasting in the origin of the knobby facies. The uniform distribution of the knobby facies over ~75,000 km² argues against a single landslide, or series of landslides, as a probable mechanism for debris emplacement onto the glacier. Rather, we suggest that the uniform distribution and relief of the knobby facies, as well as evidence for significant eolian modification, point to eruptive pyroclastic deposits (air fall onto the glacier surface) as a likely source for the material that composes the knobby facies. We interpret the bedrock scarp to represent supraglacial erosion, rather than the headwall of a landslide.

In summary, the knobby facies is interpreted as a sublimation till from a cold-based mountain glacier system on the basis of its (1) homogeneity, (2) knobby and hummocky morphology, (3) superposition on underlying lava-flow topography without disruption, (4) close association with the ridged facies, (5) superposition on the ridged facies, and (6) lack of melting-related features. The nature of the sublimation process means that there is a good possibility that residual ice may underlie some of the knobs or parts of the larger deposit.

**Smooth Facies**

The smooth facies inward of the knobby terrain is characterized by a series of concentric ridges tens of meters high superposed on broad lobes hundreds of meters thick (Fig. 2C). The heads of some lobes have depressions at their centers. The largest lobe origi-
nates near the vicinity of a large linear depression, a location that caused Scott and Zimbelman (1995) to interpret the facies as proglacial flows emanating from a fissure (see also Zimbelman and Edgett, 1992) or possibly as a lahar. On the basis of the MOLA topography, we found that the lobes tend to be located on highs and to descend into adjacent lows, suggesting that the lobes did not originate as proglacial flows originating in deep depressions.

On the basis of the general morphology of these deposits as revealed in the MOLA and image data and their spatial association with the ridged and knobby facies, we have explored glacial analogues for these features. We find that rock-glacier deposits provide a very compelling analogue for these lobate features (Martin and Whalley, 1987; Whalley and Martin, 1992). Rock glaciers are commonly capped by lobate debris-covered deposits and are found in alpine environments. Rock glaciers range from ice plus rock mixtures to thin, debris-covered glaciers where ice might be preserved for considerable periods of time owing to the insulating effects of the debris. Rock glaciers form when a core of glacial ice is progressively buried by a thick debris mantle; formation is favored by high debris accumulation rates and low ice velocities, conditions common in an advanced state of glacial retreat (Whalley and Martin, 1992). For most rock glaciers in the Dry Valleys region of Antarctica, debris-over buried glacier ice thickens progressively down ice flow (Fig. 2F). Rock glaciers move downslope as a result of the deformation of internal ice or frozen sediments and are characterized by surface ridges and furrows.

On the basis of the similarity of the surface morphology and geomorphic setting of the smooth facies with terrestrial rock glaciers (Steig et al., 1998), as well as its spatial relationship with knobly sublimation till and distal moraines, we interpret this unit to be composed of rock glaciers formed in the proximal parts of the fan-shaped deposit, perhaps during the waning stages of the ice-sheet evolution. In this regard, the spoon-shaped depressions at the head of the rock-glacier lobes likely reflect surface lowering due to excess sublimation; such depressions are a common feature of terrestrial rock glaciers given that debris cover may be relatively thin at rock-glacier heads (Potter, 1972) (Fig. 2F). In the case of Asria Mons, it is unlikely that such hollows would form if the lobes were pyroclastic flows. Pyroclastic flows generally thin progressively away from the source. The sharp ridges at the head of major lobes on Asria Mons imply active flow and suggest the presence of buried glacier ice.

CONCLUSIONS

We interpret the unusual Amazonian-aged, fan-shaped deposit covering ~180,000 km² of the western flank of Arsia Mons as the remnant of a mountain glacier. In this scenario, the outer parallel-ridge zone is interpreted to be distal drop moraines formed from the lateral retreat of cold-based glacier ice and the knobly facies to be proximal hummocky drift resulting from the sublimation, decay, and downwasting of this ice (a sublimation till). The arcuate lobes in the proximal zone are interpreted to be rock-glacier deposits, formed by flow deformation of debris-covered ice; some deposits may still have ice cores. We find little evidence for meltwater features in association with any facies, and thus conclude that the glacier ice was predominantly cold based throughout its history and ablation was largely by sublimation. Similar deposits are seen on Pavonis and Ascrasaurus Montes.

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REFERENCES CITED

Denton, G.H., and Marchant, D.R., 2000, The geological basis for a reconstruction of a grounded ice sheet in McMurdo Sound, Antarctica, at the last glacial maximum: Geografiska Annaler, v. 82, p. 167–211.

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