

COLD-BASED MOUNTAIN GLACIERS ON MARS: WESTERN ARSIA MONS FAN-SHAPED DEPOSITS: J.W. Head¹ and D.R. Marchant²; ¹Dept. of Geol. Sci., Brown Univ., Providence, RI 02912 USA; ²Dept. of Earth Sciences, Boston Univ., Boston, MA 02215 USA.

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 lobe, or fan-shaped deposit on their western flanks. These deposits, as exemplified by those on Arsia Mons (e.g., 1, 2), usually contain three facies (Figs. 1a, 2a,b,c) and various hypotheses have been proposed for their origin including one or more of the following: lahars, debris avalanches, landslides, pyroclastic flows, and/or generally related to the advance and retreat of ice (e.g., 3).

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, on-going 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 ([4] and references therein). 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. We outline here the deposit characteristics and use Antarctic Dry Valley analogs [4] to aid in their interpretation.

Description and Interpretation: The Ridged Facies consists of a series of over 100 concentric ridges that extend several hundred kilometers beyond the break in slope at the base of Arsia Mons (Fig. 1a, 2a). Ridges are typically spaced about a kilometer apart and MOLA data show that individual ridges vary in height, with the outer prominent ridge reaching heights of ~50 m, while typical inner ridges are of the order of 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. 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.

One of the most distinctive characteristics of the ridged facies is its superposition on a subjacent impact crater and lava flows without apparent modification ([1-3, 5-7] Fig. 1a, 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, together with the extreme regularity of the ridges suggest that the fan-shaped deposit was emplaced by a process that involved little interaction with the substrate.

On the basis of Antarctic cold-based glacial analogs [4] we interpret the ridged facies on Arsia 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 Knobby-Terrain, the next innermost facies (Fig. 1a) of the fan-shaped deposit, is comprised of a largely chaotic assemblage of hills, some as much as several kilometers across, that are sub-rounded to elongated downslope; some hills are aligned and form arcs that in general are parallel to ridges in the distal facies. The deposits that comprise the knobby terrain are very homogeneous in local areas, (e.g., Fig. 2b) and show little detailed structure as a whole. 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 further into the area of the knobby facies; it appears that 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. 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) [4], 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.

In summary, the knobby facies is interpreted as a sublimation till from a cold-based mountain glacier system on the basis of the following evidence: 1) its homogeneity, 2) its knobby and hummocky morphology, 3) its superposition on underlying lava flow topography without disruption, 4) its close association with the ridged facies; 5) its superposition on the ridged facies, and 6) its 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.

The Smooth Facies lies inward of the knobby terrain (Fig. 1a) and 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.

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 find that rock-glacier deposits provide a very compelling analog for these lobate features [4]. Rock glaciers range from ice-rock mixtures to thin, debris covered glaciers where ice might be preserved for considerable periods of time due 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. For most rock glaciers in the Dry Valleys region of Antarctica, debris over buried glacier ice thickens progressively down ice flow. 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, as well as its spatial relationship with knobby sublimation till and distal moraines, we interpret this unit to be comprised 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

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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. The sharp ridges at the head of major lobes on Arsia Mons imply active flow and suggest the presence of buried glacier ice [4].

Conclusions: In summary, on the basis of terrestrial analogs of cold-based glaciers [4], 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 knobby facies to be more 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 be ice-cored. 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 Ascreaus Montes.

References: 1) J. Zimbelman and K. Edgett, *PLPSC* 22, LPI, 31, 1992; 2) D. Scott and J. Zimbelman, *USGS Misc. Inv. Map I-2480*; 3) B. Lucchitta, *Icarus*, 45, 264, 1981; 4) D. Marchant and J. Head, *PLPSC* 34, LPI, this volume; 5) R. Williams Jr., *GSA*, 10, 517, 1978; 6) F. Anguita and F. Moreno, *Earth Moon and Planets*, 59, 11, 1992; 7) J. Helgason, *Geology*, 27, 231, 1999.

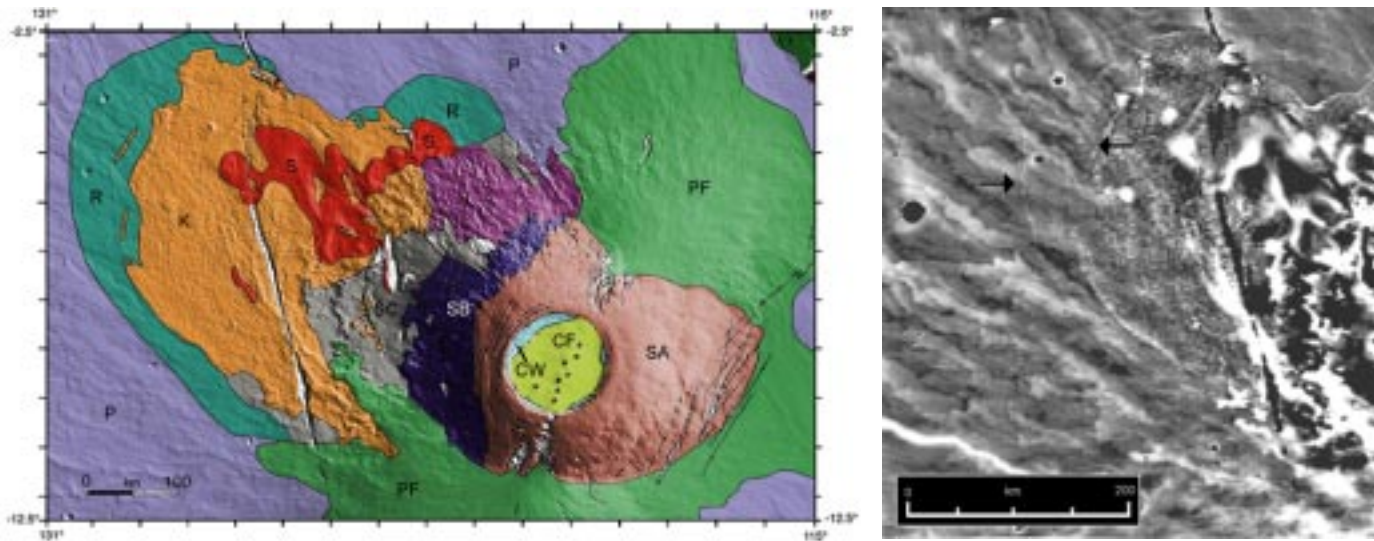


Figure 1. a) Geological sketch map of the western Arsia Mons fan-shaped deposit (modified from Zimbelman and Edgett, 1992) superposed on a MOLA topographic gradient map (fan-shaped deposits: R, ridged; K, knobby; S, smooth) (other adjacent deposits: SA, shield; SB, degraded western flank; SC, smooth lower western flank; CF, caldera floor; CW, caldera wall; PF, flank vent flows from Arsia Mons; P, undivided Tharsis plains). b) Detrended MOLA topography of western Arsia Mons (regional slopes have been removed; lighter is relatively steeper topography and darker is relatively shallower topography; black is no data presented). Note that the lava flows clearly extend underneath the ridged and knobby facies and are undisturbed (compare to a). Arrows show inner and outer margins of ridged facies.

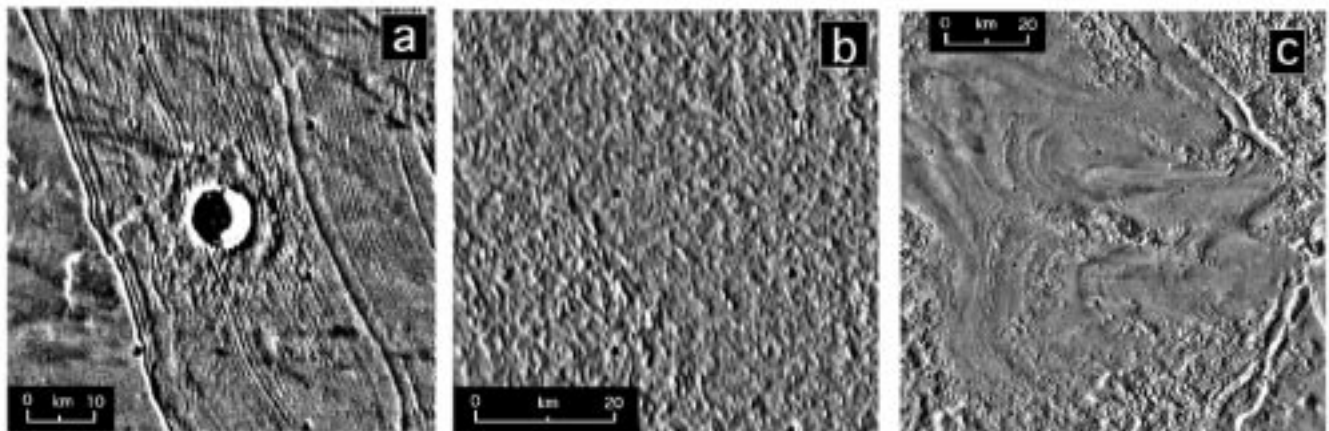


Figure 2. Facies of the fan-shaped deposit. a) Ridged facies, interpreted as drop moraines; b) Knobby facies, interpreted as sublimation tills; c) Smooth facies, interpreted as rock glaciers; (Viking Orbiter images)