MOUNTAIN GLACIERS ON MARS? CHARACTERIZATION OF WESTERN THARSIS MONTES FAN SHAPED DEPOSITS USING MGS DATA.

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Introduction: Tharsis Montes cap the broad Tharsis Rise (Fig. 1), 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. On the basis of their unusual nature and superposition relationships, they have attracted attention since they were first described from Mariner 9 and Viking data [1]. These deposits, as exemplified by those on Arsia Mons [e.g., 2,3], usually contain three facies: 1) An outermost ridged facies, consisting of a broad thin sheet characterized by numerous ridges, 1->10 km in length, and spaced a few hundred meters to several kilometers apart, that extend over topographic barriers without obvious deflection. 2) A knobby facies, which forms an extensive area of chaotic terrain that consists of subrounded several-kilometer-diameter hills; some hills are elongated downslope, and others form chains that are parallel to subparallel to the ridges in the ridged facies. 3) A smooth facies, which contains arcuate lineations and diffuse to lobate margins; the smooth facies appears to overlie areas of the knobby facies.

As summarized in [3], the fan-shaped deposits have been variously compared to landslide deposits such as those seen along the walls of Valles Marineris [e.g.,4,5], solifluction lobe-like features observed locally around the bases of hills [e.g. 6,7], deposits interpreted to be of pyroclastic origin associated with large volcanoes like Alba, Elysium and Hecates [e.g.,8,9], and glacially-related processes [e.g.,10,11]. Specifically, previous interpretations of these deposits have included [3]: "(1) large landslides initially deposited on ice-covered plains [12], (2) ash-flow tuffs or slump material [13], (3) fluid volcanic flows modified by wind erosion [14], (4) recessional moraines emplaced by former local ice caps [11], (5) landslides or debris flows [15], (6) volcanic-debris avalanches resulting from either slope failure or explosive volcanism [16], and (7) pyroclastic deposits [2]."

Scott and Zimbelman [3] synthesize the various hypotheses on the origin of these features into three broad categories of candidate processes of origin: "(1) mass movement (including landslides, volcanic-debris avalanches, and lahars), (2) volcanism (pyroclastic flows and ash flows), and (3) glacial and periglacial activity (erosion and deposition caused by the advance and retreat of ice)." In a summary of the characteristics of the Tharsis Montes, Zimbelman and Edgett [2] also point out that any hypothesis for the origin of the flanking features must successfully explain: 1) the complex arrangements of the associated landforms, and 2) the restricted occurrence of the deposits on the western flanks of the edifices.

Two new developments are the basis for the research reported in this analysis. First, new Mars Global Surveyor data (e.g., MOLA altimetry, MOC images, and TES thermal emission data) 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. Secondly, glaciers and glacial deposits have become much more well known and understood. For example, it is known (summarized in [17]) that following emplacement as snow, the temperature of accumulated materials are influenced by heat exchange with the atmosphere, the geothermal heat flux, and frictional heat generated by flow. Temperature profiles in the accumulating snow and ice depend on the balance of heat from these three sources, and this permits the thermal classification of glacier ice into temperate ice, which is at the pressure melting point (Tm), and cold ice, which is below the pressure melting point. This then leads to a simple classification of glaciers to include 1) Temperate glaciers, which are generally everywhere at the Tm (wet-based), 2) Polar glaciers, which are below the Tm throughout, and are frozen to underlying beds (cold-based), and 3) Subpolar glaciers, which are temperate in their inner regions, but have cold-based margins. Of course, this classification is simplistic in that the thermal conditions may vary in both space and time. On the basis of present surface temperatures on Mars, the vast majority of the surface is likely to be such that any glaciers will be cold-based. Recently, the nature and evolution of terrestrial cold-based glaciers have become much better known, particularly through the Antarctic exploration program and research in the Antarctic Dry Valleys [e.g., 18,19], which represent conditions on Earth that are likely to be most similar to those of the cold, hyperarid regions of Mars.

In this contribution we describe the background and previous work, and then use new Mars Global Surveyor data to characterize the deposits and their relationships to the rest of the volcano, and we then explore and test the hypothesis that these deposits might be the result of glacial activity [e.g., 11], and also assess other theories of origin. We particularly emphasize new knowledge on the nature and evolution of cold-based glaciers and their relationships to wet-based glaciers. We first focus on the most extensive and well-developed deposit on the Tharsis Montes, on the western flank of Arsia Mons.

Description, setting and previous work: In a comparison and synthesis of the Tharsis Montes, Zimbelman and Edgett [2] described the lobe or fan-shaped deposit west-northwest of Arsia Mons as consisting of four basic terrain types (Fig. 2); a ridged unit (r) along the margin of the lobe, a knobby terrain (k), a lobate terrain (l), consisting of interwoven linear segments defined by lobate flow fronts, and a smooth component (s), which was interpreted to lie on top of all other terrains (including two large graben that extend across the lobe). A series of irregular, arcuate, outward-facing scarps also occurs along the upper parts of the edifice just below the summit. As noted in [2] the ridged unit (r) was superposed on the surrounding plains, but that superposition relationships were unclear with the knobby (k) and lobate (l) terrains.

Zimbelman and Edgett [2] interpreted the lobate terrain (l), which is confined to the northern portion of Arsia and is at the highest elevations, to be lava flows that emanated from the basal scarp. They note that the superposition of the smooth unit on all other terrains and its close association with the irregular collapse depressions suggests that these features may be the deposits from pyroclastic eruptions emanating from the collapse features. The irregular, outward-facing scarps were interpreted to be the result of mass-wasting. Although [1] had interpreted these scarps to be the headwall of a landslide that they interpreted to have formed the lobate deposit, [2] noted that the missing volume was at least an order of magnitude less than that of the deposit itself. They further note that a landslide origin must account for the very large size and length of the lobes as well as the lack of obvious sources of sufficient volume. While acknowledging that large circum-edifice landslides are seen on Mars around Olympus Mons, they point out that these are morphologically different from those on Tharsis Montes.

Zimbelman and Edgett [2] found that the suggested glacial origin for the deposits was not compelling because of the lack of similarity between the lobes and the layered and pitted terrains found around the martian polar caps, and the location of the fan-shaped deposits near the equator where ice accumulation is not currently predicted (e.g.,[20]). They proposed that pyroclastic activity should be considered as an additional factor in the formation of the lobes, with the smooth unit lineations and lobateness the result of pyroclastic deposits emplaced from sources within the graben, with this phase of activity perhaps generated by release of lithostatic load resulting from sliding events (see also [21]).

Lucchitta [11] compared an array of cold-climate features on Earth to selected features on Mars. Among the comparisons, she cited the continuous parallel ridges at the distal edge of the Arsia Mons fan, and their similarities to structures on moving ice sheets. She noted, however, the apparent superposition relationships of the ridges on an underlying, apparently undisturbed crater, relationships that suggested that the crater had not been deformed by moving ice. Nonetheless, she drew attention to the fact that the ridges resembled some terrestrial moraines [10] and compared them to washboard moraines on the forefield of Skeidararjokull outlet glacier in Iceland [see 22]. Lucchitta [11, p. 284] found these comparisons to be compelling enough to suggest that the fan-shaped deposits could have "resulted from local ice caps that formed on the volcanoes from mixtures of emanated volatiles and erupted ash."

Anguita and Moreno [23] examined the Arsia Mons fan-shaped deposit and outlined features (similar to the smooth facies of both [2,3]) that they interpreted to be folds about 50 km across generated by strike-slip movement on Aganippe Fossa and other faults. In this scenario, sinistral strike-slip movement on these faults created the folds, which exposed layered sequences in the broader fan-shaped deposit. Anguita and Moreno [23, p. 11] take these exposures "as definitive evidence for its deposition as ice." Furthermore, they interpret the "striated terrain" (equivalent to the ridged facies of [2,3]) to be glaciotectonic ridges formed by basal tills being thrust by ice movement, and the more prominent ridges to be end moraines.

More recently, in an analysis of the origin of the Olympus Mons aureoles, [24] provided further discussion of a glacial origin for the Arsia Mons fan-shaped deposit. Following the interpretation of the washboard moraines at the Skeidararjokull margin that suggested that their "sinuous form seems to reflect the contour of the glacier margin and indicates that these moraines are formed at the margin and not underneath the glacier" [22, p. 311], it was proposed [24] that the ridged facies represented a recessional moraine where a glacier retreated over a 60 km distance, followed by slower recession to produce the rugged hummocky and smooth terrain, which [24, p. 232] interpreted to be "dead-ice with a relatively thick cover of wind-blown dust". Furthermore, he suggested that other features on the summit of Arsia could be interpreted to represent the presence of a thick ice cap on the summit itself.

Summary and Synthesis of the Fan-Shaped Deposits on Western Arsia Mons: The unusual Amazonian-aged, fan-shaped deposit covers ~180,000 km^2 of the western flank of Arsia Mons. It consists of three components: 1) an outermost ~60-90 km wide distal zone of over 100 parallel raised ridges (Fig. 3); 2) a medial ~80-300 km wide zone of rough, hummocky topography (Fig. 4); 3) a proximal zone up to ~150 km wide abutting the upper flanks of Arsia and consisting of arcuate and lobate flow-like deposits (Fig. 5). Upflank are several sinuous outward-facing scarps, rough near-summit topography, and pits and elongate troughs. Within the fan shaped deposit are NNW-striking, graben-like elongate depressions. The distal ridged deposits are superposed on lava flows and a large impact crater and underlying lava flows can be traced back underneath the medial hummocky unit to the graben structure.

Using new MGS data and Earth analogs appropriate for Mars, we explored the hypothesis that the deposit is the remnant of a mountain glacier formed on the western flank of Arsia Mons (e.g., [3]). Conditions during the recent geological history of Mars suggest that glacial ice should commonly be below the pressure melting point, and thus analogous to polar glaciers, which are frozen to underlying beds (cold-based), and move by internal deformation, producing no record of basal scour or extensive meltwater features. Glaciers in the Antarctic Dry Valleys may be most appropriate terrestrial analogs, and we find many similarities between them and the western Arsia fan-shaped deposits.

We interpret the outer parallel ridge zone to be distal dump moraines formed from the lateral retreat of a cold-based glacier, and the hummocky facies to be proximal hummocky moraines resulting from the sublimation, decay and downwasting of the ice sheet (a sublimation till). The arcuate structures in the proximal zone are interpreted to be rock glaciers, formed by lobate flow deformation of debris-covered ice surfaces; some rock glaciers may still be ice-cored. We find little evidence for melting features in association with the deposit, and thus conclude that it was predominantly cold-based throughout its history. In summary, we find abundant evidence to support the interpretation that the fan-shaped western Arsia Mons deposit was formed by a cold-based mountain glacier. Similar deposits are seen on Pavonis and Ascraeus Montes.

Stratigraphic relations show that the medial hummocky unit partly overlies the distal parallel ridged unit; we interpret this to mean that there was at least one phase of readvance following retreat of a significant part of the cold-based glacier. Contemporaneous volcanic eruptions suggest that tephra may be the main non-ice component of the glacial deposits. If the glacial interpretation is correct, this means that at some time during the Amazonian conditions were conducive to the accumulation of ice on the western flanks of the Tharsis Montes, and that subsequently the ice largely disappeared. Possible causes of ice accumulation could be 1) extremes in orbital parameters, which could result in sublimation of polar deposits and deposition in equatorial regions, or 2) locally increased water supply to the atmosphere, perhaps coincident with Amazonian-aged catastrophic outflow in nearby Elysium and Amazonis Planitia, orographic upwelling, and deposition. The presence of rock glaciers suggests that some ice may still exist in the shallow subsurface, and may preserve a record of the Amazonian atmosphere and Tharsis Montes tephrochronology.

References: 1) M. Carr, JGR, 78, 4049, 1973; M. Carr et al., JGR, 82, 3985, 1977; 2) J. Zimbelman and K. Edgett, PLPSC 22, LPI, 31, 1992; 3) D. Scott and J. Zimbelman, , USGS Misc. Inv. Map I-2480, 1995; 4) B. Lucchitta, JGR, 84, 8097, 1979; 5) B. Lucchitta et al., Mars, Arizona, 453, 1992; 6) D. Scott, Icarus, 34, 479, 1978; 7) S. Squyres et al., Mars, Arizona, 523, 1992; 8) C. Reimers and P. Komar, Icarus, 39, 88, 1979; 9) P. Mouginis-Mark et al., BV, 50, 361, 1988; 10) R. Williams, GSA, 10, 517, 1978; 11) B. Lucchitta, Icarus, 45, 264, 1981; 12) D. Wilhelms, JGR, 78, 4084,, 1973; 13) M. Carr, USGS Misc. Inv. Map I-893,, 1975; 14) H. Masursky et al., USGS Misc. Inv. Map I-896, 1978; 15) M. Carr, The Surface of Mars, Yale, 1981; 16) D. Scott and K. Tanaka, USGS Misc. Inv. Map I-1802-A, 1986; 17) D. Benn and D. Evans, Glaciers and Glaciation, Arnold, 1998; 18) D. Sugden et al., Nature, 376, 412, 1995; 19) D. Marchant et al., GSAB, 114, 718, 2002; 20) C. Farmer et al., JGR, 82, 4225, 1977; 21) K. Edgett, LPSC 20, 256, 1989; 22) S. Thorarinsson, Jökull, 17, 311, 1967; 23) F. Anguita and F. Moreno, EMP, 59, 11, 1992; 24) J. Helgason, Geology, 27, 231, 1999.

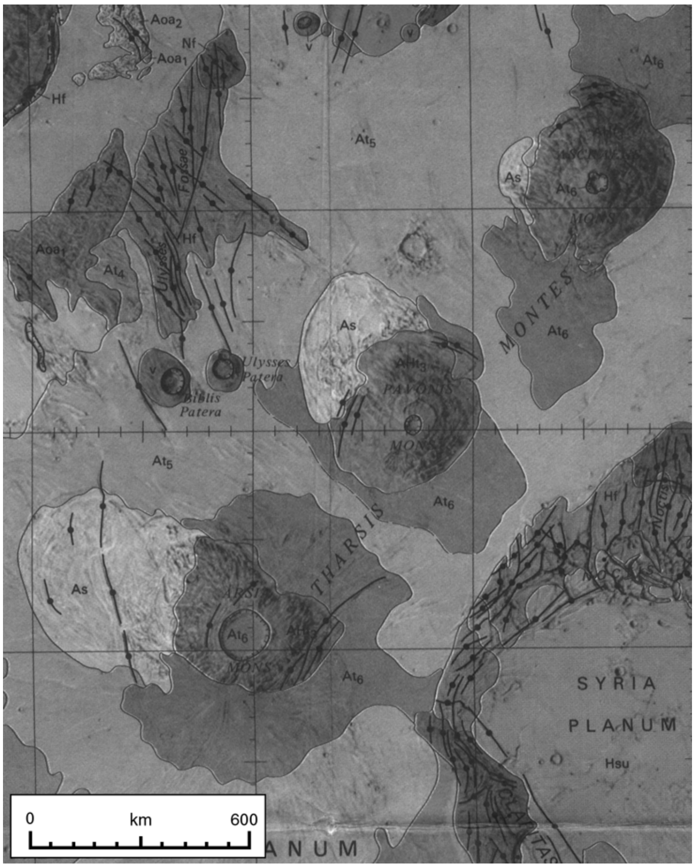

Figure 1. Location map of Tharsis Montes and the lobe or fan-shaped deposits along their western flanks (from [16]).

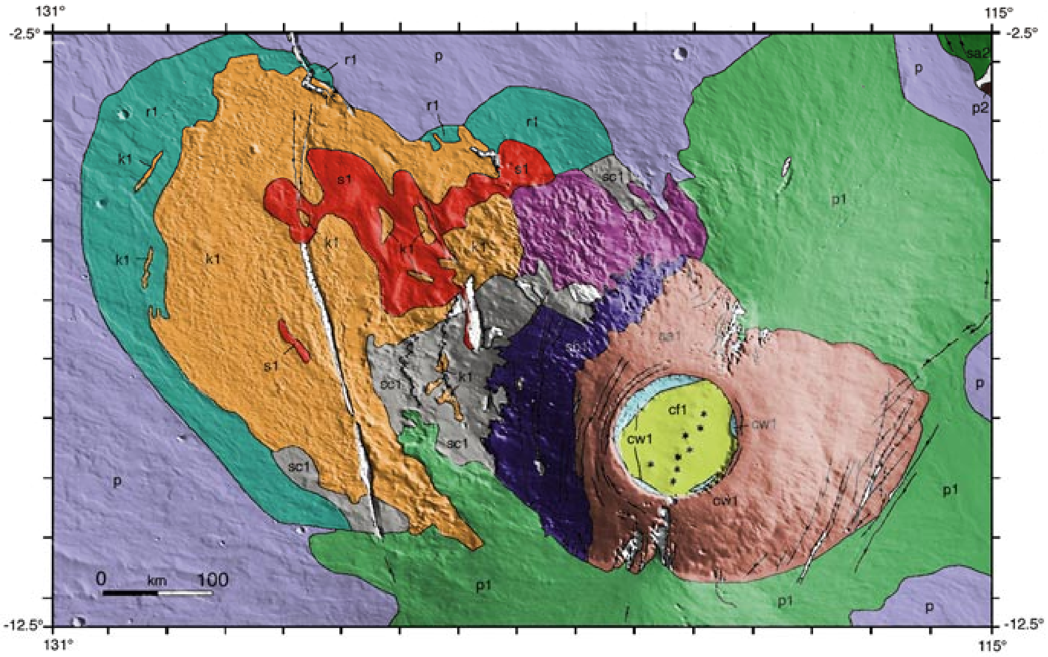

Figure 2. Geologic map of Arsia Mons and deposits [2] with underlying MOLA gradient map of region.

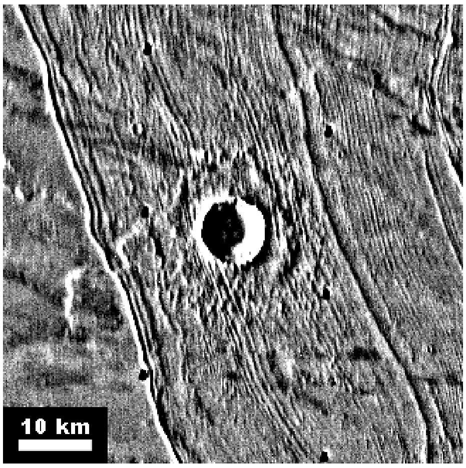

Figure 3. Viking Orbiter image of the ridged facies of the fan-shaped deposit.

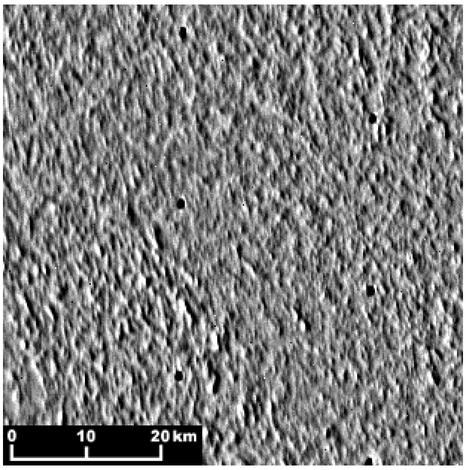

Figure 4. Viking Orbiter image of the knobby facies of the fan-shaped deposit.

Figure 5. Viking Orbiter image of the smooth facies of the fan-shaped deposit.