COLD-BASED GLACIERS IN THE WESTERN DRY VALLEYS OF ANTARCTICA: TERRESTRIAL LANDFORMS AND MARTIAN ANALOGS. J. W. Head[1] and D. R. Marchant[2], [1]Department of Geological Sciences, Brown University, Providence, RI 02912 james_head@brown.edu, [2]Department of Earth Sciences, Boston University, Boston, MA 02215.

Introduction: Basal-ice and surface-ice temperatures are key parameters governing the style of glacial erosion and deposition. Temperate glaciers contain basal ice at the pressure-melting point (wet-based) and commonly exhibit extensive areas of surface melting. Such conditions foster basal plucking and abrasion, as well as deposition of thick matrix-supported drift sheets, moraines, and glacio-fluvial outwash. Polar glaciers include those in which the basal ice remains below the pressure-melting point (cold-based) and, in extreme cases like those in the western Dry Valleys region of Antarctica, lack surface melting zones. These conditions inhibit significant glacial erosion and deposition. An intermediate classification of subpolar glaciers includes those with wet-based interiors and cold-based margins.

Results from field-based research in Antarctica show that ancient landscapes are preserved beneath cold-based glacier ice. These results, along with new insights from quantitative measurements of glacial abrasion [e.g., 1], have prompted us to re-evaluate some Martian landforms in terms of glacial processes. As background, we here summarize the formation of drop moraines, sublimation tills, and rock glacier deposits associated with cold-based glaciers in the Dry Valleys of Antarctica, and then outline the case for similar glacial landforms along the western flanks of the Tharsis Montes, specifically Arsia Mons.

Terrestrial Landforms: Basal sliding, basal entrainment, and transport of basal debris towards the glacier base are three fundamental requirements for significant glacier erosion. Basal sliding requires subglacial meltwater, a property controlled largely by the thermal regime of the glacier. At the base of wet-based glaciers, debris is entrained chiefly through regelation, a process whereby basal meltwater is frozen onto the glacier base. Regelation normally occurs where the basal-ice temperature fluctuates about the pressure-melting point. In such cases, small bedrock obstacles yield pressure variations that induce basal-ice melting and refreezing. Refreezing of “dirty” meltwater entrains basal debris. At sites of persistent pressure melting, the continued downward transport of basal debris towards the bedrock interface results in elevated rates of bedrock erosion. Such processes result in overdeepened basins found commonly beneath cirque and valley glaciers. Although simplified, the above represents the classic scenario for wet-based, subglacial erosion [2-6]. Recent studies show that some basal debris may also be entrained beneath cold-based ice [7]. Debris may be entrained through rotation of loose bedrock by glacier flow [5] or by freezing of interfacial meltwater films (<<1 mm thick) at subfreezing temperatures [1, 8]. Theoretical and empirical studies show that liquid water at the base of glaciers can exist in stable equilibrium at subfreezing temperatures [8]. The magnitude of erosion capable from freezing of such subglacial meltwater, for example where measured in Antarctica, is as little as 9×10^{-7} to 3×10^{-6} m yr^{-1} [1]; typically less than the rate of aeolian erosion.

Although cold-based glaciers do not erode their underlying substrates appreciably, they do deposit characteristic landforms [9]. The material within these landforms originates from supraglacial debris, commonly rockfall and/or volcanic ejecta that falls onto the glacier surface. Angular and lacking evidence for subglacial abrasion, these rockfall and volcanic particles flow passively through the ice toward glacier margins. The resulting landforms (e.g., drop moraines, sublimation till, rock-glacier deposits) are perched on existing topography. Sharp basal contacts and undisturbed underlying strata are hallmarks of cold-based glacier deposits [10].

Drop moraines. The term drop moraine is used here to describe debris ridges that form as supra- and englacial particles are dropped passively at margins of cold-based glaciers (Fig. 1a and 1b). Commonly clast supported, the debris is angular and devoid of fine-grained sediment associated with glacial abrasion [8, 10]. In the Dry Valleys, such moraines may be cored by glacier ice, owing to the insulating effect of the debris on the underlying glacier. Where cored by ice, moraine crests can exceed the angle of repose. In plan view, drop moraines closely mimic the pattern of former ice margins, though moraine width may vary spatially, owing to the characteristic inhomogeneity in the distribution of supraglacial debris (excepting volcanic airfall debris). Debris is generally thickest in regions near (or down ice flow from) bedrock cliffs.

Sublimation till. Sublimation along the ice/atmosphere interface may bring englacial debris passively to the ice surface. The rate of ice sublimation slows as the evolving sublimation till thickens, eventually insulating the underlying ice by retarding vapor diffusion and thermal change. Many sublimation tills in the western Dry Valleys region of Antarctica are underlain by glacier ice, even though some are in excess of 8.1 Ma [12,13] (Fig. 2a and 2b). Differential flow of underlying glacier ice may result in distinct surface lobes of sublimation till (see also below). In addition, thermal contraction near the surface of the buried glacier commonly initiates a network of surface polygons that cut the till, the relief of which is controlled in part by variations in till porosity and permeability [13].

Rock-glacier deposits. In the western Dry Valleys region of Antarctica, rock glaciers form as sublimation concentrates debris on the surface of active glaciers. Continued flow of the underlying glacier through internal deformation produces ridges and lobes of sublimation till atop the glacier (Fig 3a and 3b). The thickness of this debris increases down ice flow, as material is continually added to the base of the sublimation till as it moves down valley. In general, rock-glacier formation is favored by high debris accumulation rates and low ice velocities, conditions common in an advanced state of glacial retreat [14]. Spoon-shaped hollows that commonly form at the head of many terrestrial rock glaciers [15, 16] likely arise as incomplete debris covers there facilitate excess sublimation over that beneath more extensive tills down valley.

Martian analogs: 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., 17, 18), usually contain three facies (Figs. 4a, 5a,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., 19).

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. 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 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. 4a, 5a). 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 ([17-19, 20-22] Fig. 4a, 5a). We used detrended MOLA data to examine the local topographic relationships (Fig. 4b) 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. 5a, and an earlier phase of lava flows, Fig. 4a), 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 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. 4a) of the fan-shaped deposit, is comprised 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. The deposits that comprise the knobby terrain are very homogeneous in local areas, (e.g., Fig. 5b) 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. 4b). 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. 5e), 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. 4a) and is characterized by a series of concentric ridges tens of meters high superposed on broad lobes hundreds of meters thick (Fig. 5c). 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. 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 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.

Conclusions: In summary, on the basis of terrestrial analogs of cold-based glaciers, we interpret the unusual Amazonian-aged, fan-shaped deposit covering ~180,000 km^2 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 Ascraeus Montes.

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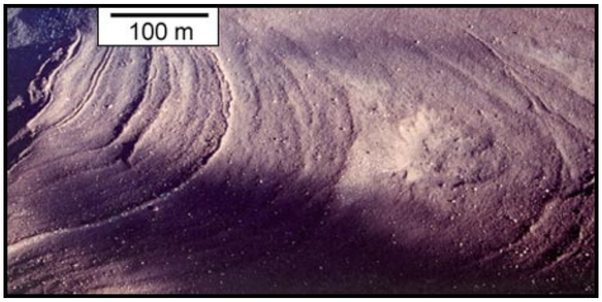


Figure 1a. Drop moraines, on the floor of lower Arena Valley, deposited from former fluctuations of Taylor Glacier. The oldest moraines are > 1.2 Ma [9].

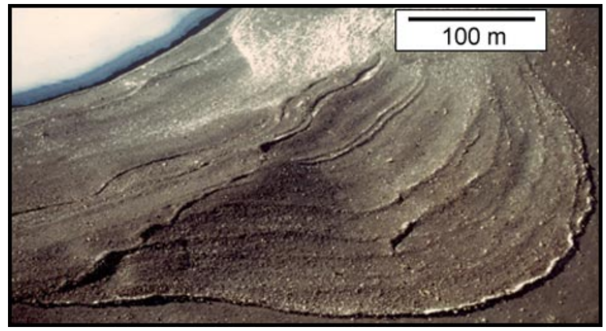


Figure 1b. Close-up view of drop moraines in lower Arena Valley (Taylor Glacier in upper left-hand corner). The outermost moraine stands 3 m above the surrounding valley floor.

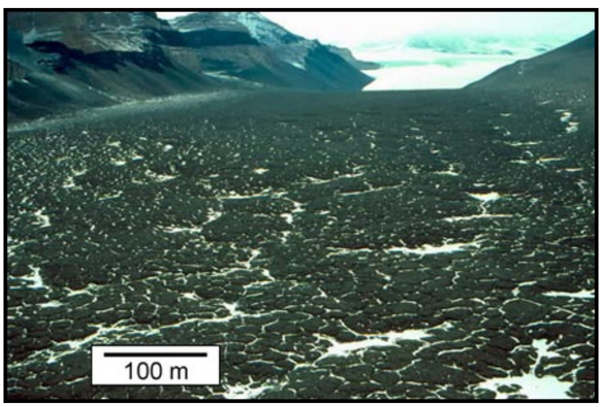


Figure 2a. Oblique air view of central Beacon Valley. The flat valley floor, lined with polygons, is underlain by glacier ice > 8.1 Ma [12, 13].

Figure 2b. Glacier ice, >8.1 Ma [12, 13], buried beneath 50-cm-thick sublimation till on the floor of central Beacon Valley.

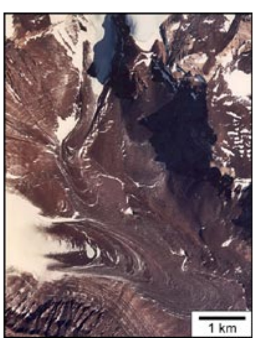


Figure 3a. Rock glaciers at the head of Beacon Valley, Antarctica. The dolerite-rich drift that covers these glaciers is <1 m thick.

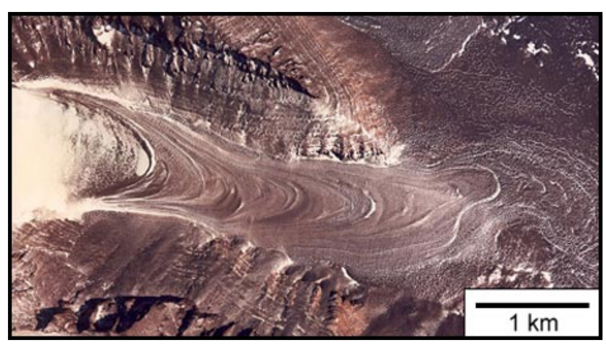
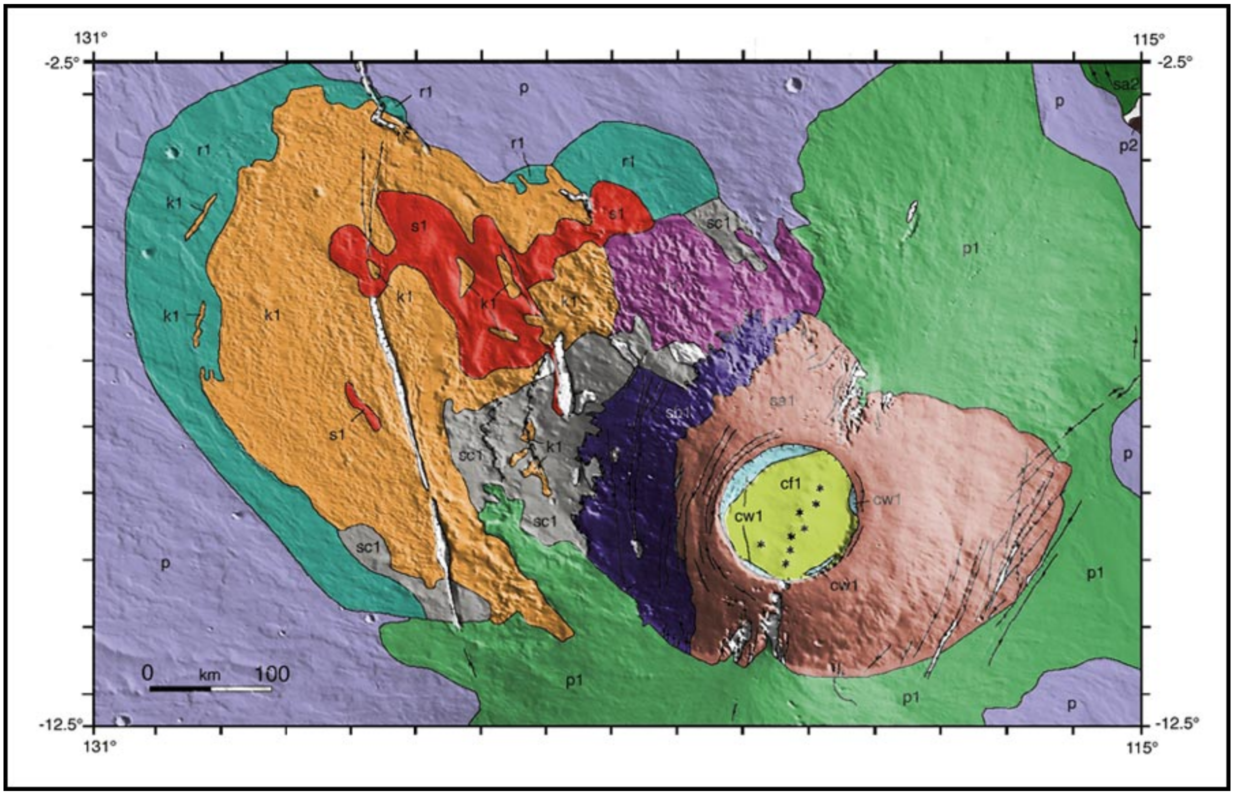


Figure 3b. The Mullins Valley rock glacier, upper Beacon Valley. This rock glacier, about 6 km in length, is as much as 700 ka near its distal end.



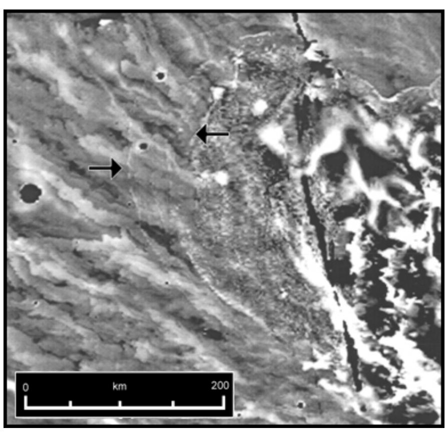


Figure 4a (above). Geological sketch map of the western Arsia Mons fan-shaped deposit (modified from [17]) superposed on a MOLA topographic gradient map (fan-shaped deposits: R, ridged; K, knobby; S, smooth) (other adjacent deposits: SA, shield; SB, degraded western flank; SC, smooth lower western flank; CF, caldera floor; CW, caldera wall; PF, flank vent flows from Arsia Mons; P, undivided Tharsis plains).

Figure 4b (left). 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 4a). Arrows show inner and outer margins of ridged facies.

Figure 5 (below). 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)