OLYMPUS MONS FAN SHAPED DEPOSIT MORPHOLOGY: EVIDENCE FOR DEBRIS GLACIERS.

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Introduction: Olympus Mons is the largest volcano on Mars, rising over 25 km above the surrounding plains and with a basal diameter greater than 600 km. It is surrounded by a basal escarpment up to 6 km tall. Extending up to 1000 km beyond this scarp are lobes of ridged materials known as the aureole [1, 2]. Superimposed upon the west and northwest aureole deposits at the base of the escarpment are lobate features which are often interpreted to be landslide debris aprons [2, 3].

In 1981, Lucchitta [4] demonstrated that the morphology of these marginal fan shaped deposits as revealed in Viking imagery is very similar to terrestrial glaciers. The location of these deposits is shown in Figure 1. The fan shaped deposits found on the northwest flank of Olympus Mons show long, even, curvilinear ridges which are subparallel to the deposit margins. These ridges sharply contrast with those associated with landslide deposits, which are characterized by longitudinal groves or transverse ridges. The ridges on the northwest flank debris apron exhibit similar morphology to ridges of moraine material found near the margins of terrestrial glaciers (Figure 5b in [4]). An additional deposit found at the base of the west scarp displays a tongue-shaped center with subparallel lobate ridges towards the margins. These ridges are superposed on the surrounding aureole and are not deflected by the topography; thus Lucchitta interprets them to be draped over the surface as a debris-rich or rock glacier decayed [4].

In this study we expand upon Lucchitta's hypothesis. A range of glacial emplacement mechanisms are considered.

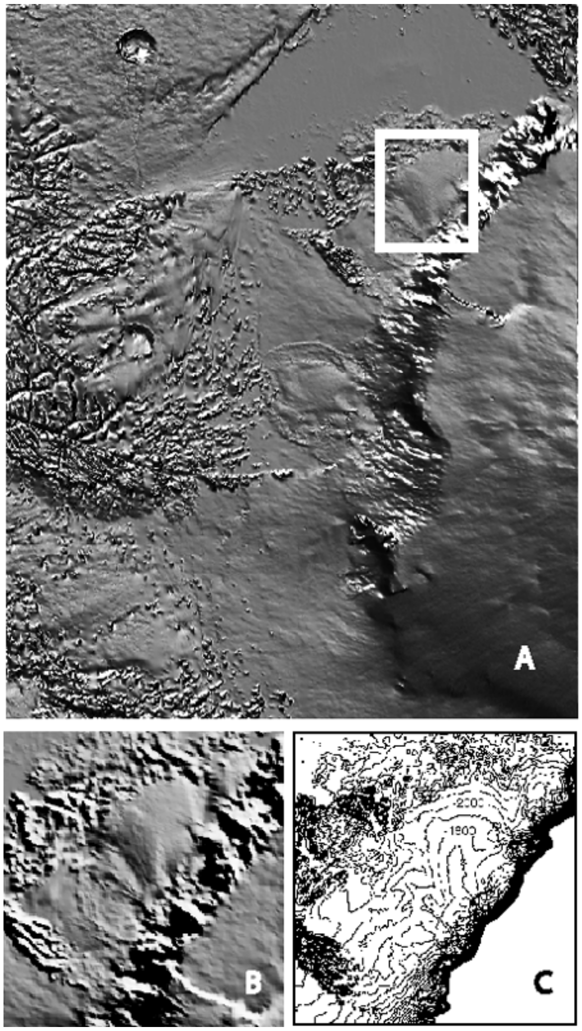

Figure 1. MOLA topographic data for the western flank of Olympus Mons. A) Topographic gradient map. Box shows the location of B and C. B) Gradient map of the northwest fan-shaped deposit. C) Contour map of same region. North is up.

Landslide Deposits: It is worthwhile to examine what the characteristics of landslide and glacial deposits are in order to interpret the fan shaped deposits. Two major landslide morphology types found on Earth, slumps and debris avalanches, have fundamentally different morphologies..

Slump deposits. These landslides have debris aprons which are wide relative to their length and have steep toes. The debris aprons themselves are cut by transverse faults to form large blocks and ridges. The source regions for slumps commonly lack a well-defined amphitheater [5].

Debris Avalanches. These landslides originate at a horseshoe-shaped depression or amphitheater [5] which often widens in the direction of movement [6]. The debris apron morphology varies internally; near the source region there are trough structures while near the distal parts there are lobe structures with hummocky terrain [7, 5]. The margins are made up of coarse debris. The surface is characterized by longitudinal grooves and transverse ridges [7, 8].

Martian Aureole Deposits The aureole is an asymmetric ring of material around Olympus Mons. This ring is made up of at least seven distinct lobes which were deposited in at least four separate instances [9]. The surface is characterized by a corrugated textured formed from curvilinear, flat topped ridges and troughs with heights of several hundred meters to a few kilometers [9], cut by graben [10, 11]. The corrugations are generally parallel to the margins of the aureole lobes [9]. It is estimated that the lobes themselves are up to 4 km thick [11]. There are also a number of linear faults and fractures in the aureoles, but they do not cut through multiple lobes or into the basement. This implies that they are mechanically detached from the underlying material [11]. Many faults indicate that the central portions of the lobes have moved forward relative to the margins of the lobes [11].

Many mechanisms have been proposed for the emplacement of these deposits, including the eroded remnant of a older, larger volcano [2], pyroclastic flows [12], and large catastrophic landslides originating at the basal escarpment [10]. A currently favored interpretation is gravity-driven landslides of lubricated material, possibly ice [9].

Estimates of the volume of the deposits range from 0.607×10^6 km^3 [10] to 3.6×10^6 km^3 [11]. This is the same order of magnitude as the volume required to reconstruct the pre-scarp flanks of Olympus Mons [10, 11]. However, the volume of the deposit is three orders of magnitude greater than that of simple martian landslides identified elsewhere [11]. Such gigantic landslides are observed on Earth as submarine landslides [5, 7]; high fluid pore pressures [10, 11] or a weak layer such as ice [9] could detach the aureole material from the basement and allow massive sliding.

Glacial Deposits: There is a wide range of glacial morphology types; the type of glacier is determined by its ice to debris ratio which is in turn determined by its source. There is much debate over the definition [for a review, see 13] as well as the formation and flow mechanisms [for a review, see 14] of many types of glaciers. The terminology used here is that of [13]; a reference diagram taken from [13] can be found in Figure 2.

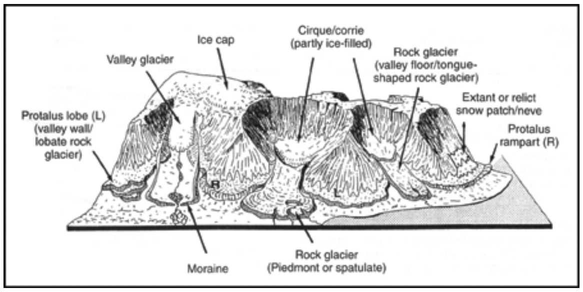

Figure 2. Types of glaciers. From [13].

Lobate rock glacier or protalus glacier. This glacier consists of single or multiple lobes originating at the base of talus slopes. The distal margin of these lobes form protalus ramparts. Protalus glaciers are at least as broad as they are long [13]. The formation of protalus glaciers is thought to be related to the presence of an abundance of interstitial ice in the talus slope, possibly changing pore pressures and allowing flow or causing deformation to occur within the ice itself if enough is present [14].

Valley glacier. This glacier is a classical glacier, a moving mass of ice which flows from an accumulation zone in a mountain range down a valley floor. Debris picked up by the glacier or deposited on top of it is carried along and deposited at the margins of the glacier once it starts to retreat in the form of a lateral or terminal moraine [15].

Rock glacier. This type of glacier is typified by a surface of rocks and angular boulders and often has ridges, furrows, and lobes on its surface. The front of an active rock glacier is at the angle of repose. Rock glaciers can have a variety of morphologies. Confined within a valley, it has a lobate body and is considered to be a shaped-shaped rock glacier. Once a rock glacier is not topographically confined, it spreads laterally and develops a spatulate shape. It is then often known as a piedmont rock glacier. Rock glaciers tend to be many hundreds of m to a few km long, and have lobate grooves on their surfaces [13, 14]

There is much debate over the formation of rock glaciers; this is because the amount of ice contained in a rock glacier is usually unknown. They may have a glacial origin, in which case they begin as valley glaciers in cirques or corries where snow is accumulated and much debris can be deposited on top from the surrounding topography [13]. This is the formation mechanism used in Figure 2. A rock glacier formed in this manner would be a thin glacier covered with a great deal of debris [14]. It is also possible that rock glaciers form as an ice-rock mixture in permafrost regions [14]. Both mechanisms would lead to deposits with the same morphology and both may occur under different conditions [14].

Debris-covered glacier. This type of glacier, not shown in Figure 2, is in between valley glaciers and rock glaciers. It is basically a valley glacier entirely covered with debris, but not to the extreme amounts of debris found in rock glaciers. This type of glacier would have a source region with some surrounding topography to serve as a source for the debris, but not the encompassing topography of a cirque as found with rock glaciers.

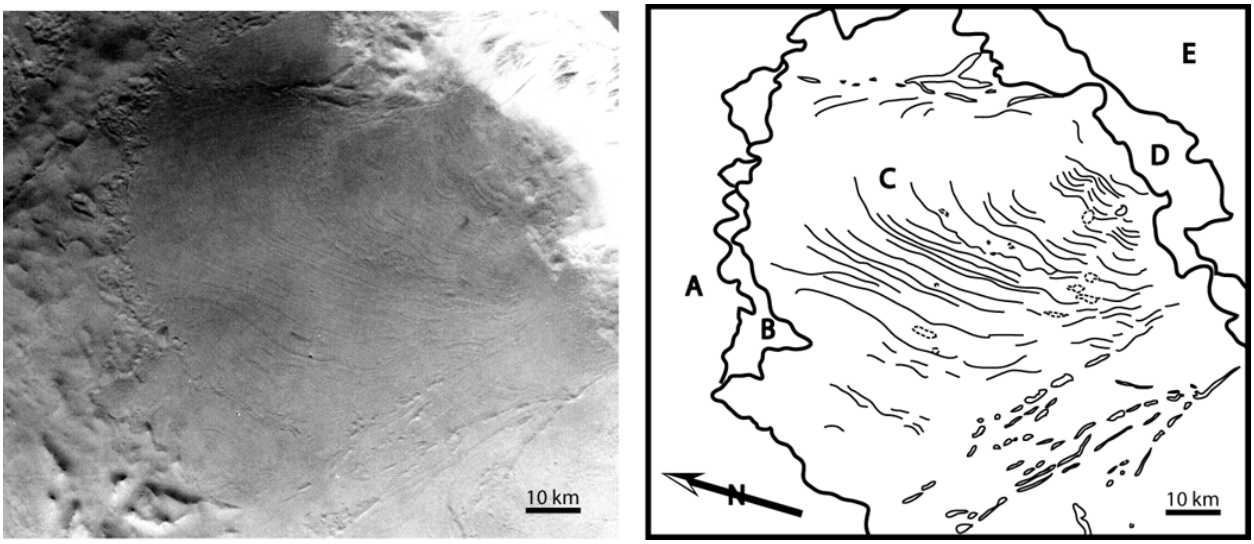

Figure 3. Fan shaped deposit at the northwest margin of the Olympus Mons basal escarpment. Left: Viking image 048B04. Right: Sketch map. Unit descriptions found in text.

Debris Apron Morphology: Figure 3 is a Viking image of a portion of the northwestern debris apron and a sketch map of this image. Five units are defined in this image. Figure 4 is the MOLA topography data for this image and the region surrounding it.

Unit A is made up of material with greater topographic relief than the rest of this image. It is part of the extensive aureole deposits described above. Unit B is located at the distal margin of the debris apron and is characterized by hummocky material.

Unit C is the fan-shaped deposit itself, a lobate unit extending approximately 90 km from the base of the scarp with regular, arcuate, subparallel ridges up to 60 km long. The deposit is approximately 600 m high. The topographic profile of this deposit is concave down. The region in the lower right of the image contains a number of linear knobs several km in length. There are several depressions in this unit, indicated by dashed lines in the sketch map. Two of these are circular and are interpreted as small impact craters. The remainder are irregularly shaped.

The corrugations and fractures which characterize the surface of the aureole deposits and terrestrial submarine landslides are not found on this unit; therefore, it is unlikely to be a landslide deposit.

Unit D is a hummocky material found at the base of the escarpment (Unit E). It is likely material eroded off of the scarp.

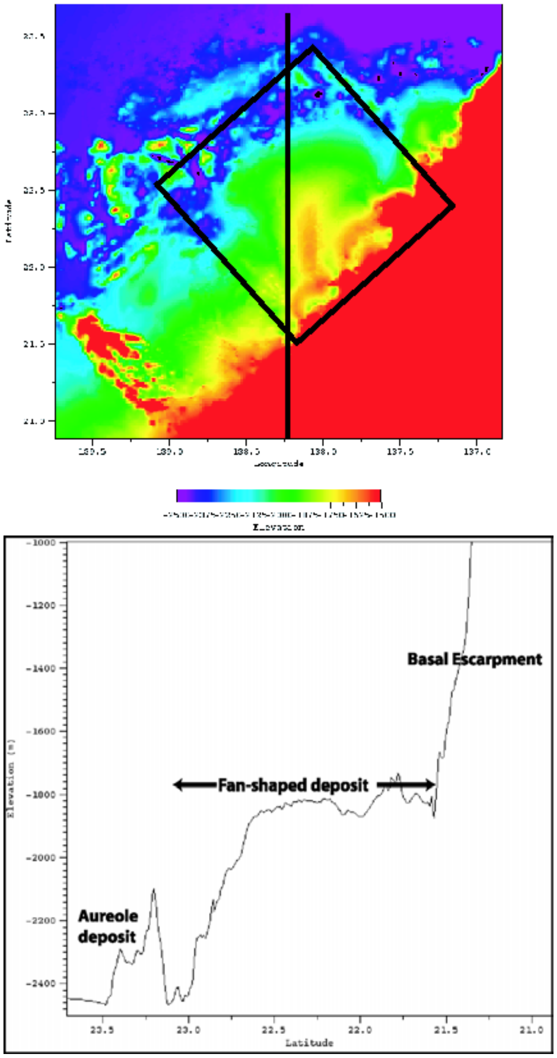

Figure 4. Top: MOLA data for fan-shaped deposit. Black line indicates location of profile. Box indicates location of Figure 3. North is up. Red region in lower right is flank of Olympus Mons. Bottom: MOLA profile.

Interpretation: We interpret the fan shaped deposits found at the base of the Olympus Mons escarpment as remnants of glaciers, in agreement with Lucchitta [4]. It is important to consider what type of glacier. The continuous, curvilinear ridges found on the surface of Unit C are very similar to rock glaciers. The source region, the basal escarpment, provides the topographic relief required to provide the debris. The linear ridges found in the lower left region of the image are interpreted as the remnants of lateral moraines, which were deposited as the glacier retreated and then eroded again as the glacier advanced. This implies several episodes of advance and retreat.

However, there is no cirque-like source for the deposits. Instead, they extend from somewhat linear segments of the basal scarp. Additionally, the fan shaped deposits are much larger than terrestrial rock glaciers; they extend many tens of km rather than up to a few km. Thus, we interpret these features to be the remnants of debris-covered glaciers, which are morphologically similar to rock glaciers but contain more ice and therefore flow more like valley glaciers and cover greater distances.

We thus envision the following scenario: glacial ice builds up on the northwestern slope of the basal escarpment. Debris from the escarpment is deposited on top of the ice. As the glacier flows to the northwest, it spreads and develops a spatulate form. Several periods of advance and retreat are recorded by the eroded lateral moraines. At the furthest extent of advance, the glacier deposited a large terminal moraine. This moraine has now degraded, perhaps by sublimation of internal ice blocks or removal of debris through aeolian erosion. This has left the hummocky material in unit B.

Discussion: Lucchitta [4] also identified glacier-like features at the nearby Tharsis Montes. Recent analysis of MOLA topography data confirm this result and conclude that cold-based glaciers were once on the west-northwest flanks of Arsia Mons [16, 17] and Pavonis Mons [18, 19]. Cold-based glaciers are made up of ice that is entirely below the melting point; thus, it flows through internal deformation and there are no melting features associated with the glacier. It is likely that most mountain glaciers on Mars would be cold-based [17].

The glacial features found around the Tharsis Montes are far more extensive than those at Olympus Mons. This implies that a greater quantity of ice was available at the Tharsis Montes. Since all of these volcanoes are in the equatorial regions, it seems likely that they were glaciated at the same time. If water ice were stable at one location, it should be stable at the others. However, the fact that Olympus Mons had smaller glaciers implies that the conditions there were not as favorable for surface ice. One possibility is that Olympus Mons was more active at the time; a higher geothermal flux in this region could prevent large build-ups of ice.

The Tharsis glaciers have more moraine features and less debris-covered glacier features than the Olympus Mons deposits. This implies that the Olympus Mons deposits had higher debris to ice ratios. This could be due to the presence of the basal escarpment. The scarp provides a source of debris that glaciers at the other deposits would not have. Other debris sources include volcanic ash and aeolian dust.

References: [1] Mouginis-Mark, P. J. et. al. (1992) in *Mars* [ed.by H. H. Kieffer et al] pp.424-452. [2] Carr, M. H. et al. (1977) *JGR 82*, 3985-4015. [3] Blasius (1976), Ph. D. thesis, California Institute of Technology, Pasadena, CA. [4] Lucchitta, B. K. (1981) *Icarus 45,* 264-303. [5] Moore et al (1989) *JGR, 94*, 17465-17484. [6] Moon, V. and Simpson, C. J. (2002) *Engineering Geology, 64*, 41-64. [7] Ablay, G. and Hürlimann, M. (2000) *J. Volc. Geotherm. Res, 103*, 135-159. [8] Laberg, J. S. and Vorren, T. O. (2000) *Marine Geology, 171*, 95-114. [9] Tanaka, K. L. (1985) *Icarus, 62,* 191-206. [10] Lopes, R. et al. (1982) *JGR, 87,* 9917-9928. [11] Francis, P. W. and Wadge, G. (1983) *JGR, 88*, 8333-8344. [12] Morris, E. C. (1982) *JGR, 87,* 1164-1178. [13] Martin., H. E. and Whalley, W. B. (1987) *Prog. Phys. Geography, 11*, 260-282. [14] Whalley, W. B. and Martin, H. E. (1992). *Prog. Phys. Geography, 16*, 127-186. [15] Benn, D. I. and Evans D. J. A. (1998) *Glaciers and Glaciation*. Arnold Publishers. [16] Head, J. W. and Marchant, D. R. (2003) *Geology, in press*. [17] Head, J. W. and Marchant, D. R. (2003) *LPSC 34*, abs 1247. [18] Shean, D. and Head, J. W. (2003) *LPSC 34*, abs 1153. [18] Shean, D. and Head, J. W. (2003) *LPSC 34*, abs 1154.