PAVONIS MONS FAN-SHAPED DEPOSIT: A COLD-BASED GLACIAL ORIGIN.

D. E. Shean[1] and J. W. Head[1], [1]Brown University, David_Shean@Brown.edu, James_Head@Brown.edu

Introduction: Each of the three Tharsis Montes volcanoes on Mars has an unusual fan-shaped deposit located exclusively to the northwest of each shield. The fan-shaped deposits of the Tharsis Montes generally share three major facies: 1) ridged facies, 2) knobby facies, and 3) smooth facies. Here we examine the Pavonis fan-shaped deposit using new Mars Global Surveyor and Mars Odyssey data. Any explanation for the origin of the fan-shaped deposits must take into account both the similarities and differences in their morphologies, their approximately similar Amazonian age, and the fact that all three occur on the west-northwestern sides of the volcanoes [1]. Based on Viking Orbiter data, several models have been proposed for their formation, including landslides [2], glacial processes [3,4,5,6] and pyroclastic flows [6]. Williams [3] and Lucchitta [4] suggest that the fan-shaped deposits consist of moraines deposited during recession of local ice caps that formed on the volcanoes from mixtures of emanated volatiles and erupted ash [4]. Scott et al [6] suggest an explanation combining glacial and volcanic processes.

We have re-examined the fan-shaped deposits utilizing new data from Mars Global Surveyor (MOLA, MOC) and Mars Odyssey (THEMIS, GRS Suite). This analysis, together with an assessment of terrestrial analogs of cold-based glaciers [7] suggests that the Pavonis fan-shaped deposit was formed by cold-based glaciers that existed in recent Martian history.

The Pavonis fan-shaped deposit (Figure 1) extends approximately 250 km northwest of the shield base along a N35°W trend [5]. The deposit ranges from 3.0-8.5 km above the Mars datum and covers an area of 75,000 km^2, approximately half of the area covered by the Arsia deposit.

***Ridged Facies*:** The ridged facies consists of a series of hundreds of concentric, parallel ridges around the distal margins of the deposit (Figure 1). The Pavonis ridged facies is characterized by a larger, 50-100 m high outer ridge with smaller 5-30 m concentric, inner ridges. The ridged facies is also observed in the central regions fan-shaped deposit, with some inner ridges only 70 km from the base of the shield. This aspect of the ridged facies is unique to Pavonis, although the Arsia ridged facies do appear to continue beneath the knobby facies [7].

Based on their morphology, we interpret these ridges as drop moraines formed at the margins of a retreating cold-based glacier [7, 8]. The fact that these ridges can be seen in proximal regions of the fan-shaped deposit suggests that at least one major phase of retreat and deposition occurred. In addition, the ridges are superposed without modification on underlying topography, including a lobate lava flow to the west. The fact that the ridged facies is observed up to elevations of 8.5 km above Mars datum on the northern flanks of Pavonis suggests that the proposed glacier covered a significant portion of the shield flanks.

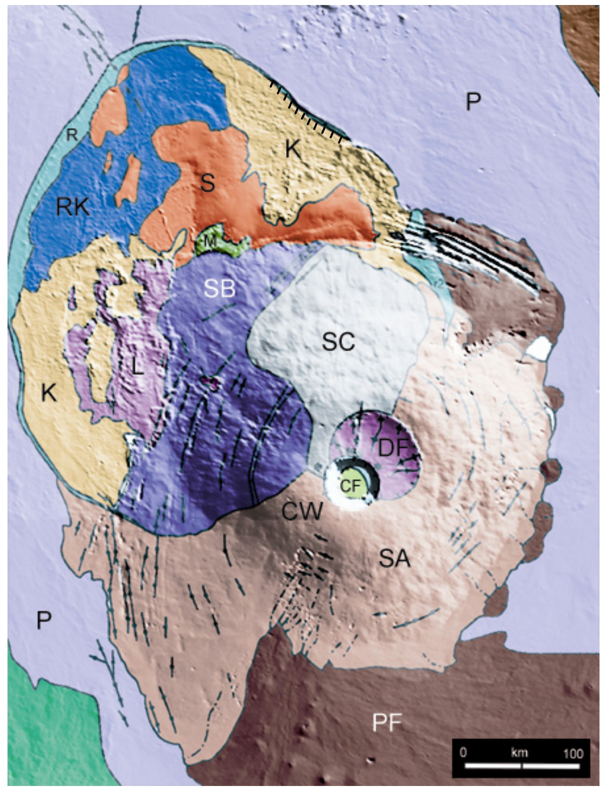

Figure 1: Geologic map of Pavonis Mons and associated fan-shaped deposit (adopted from Zimbelman and Edgett [5]), colored and draped over a MOLA shaded relief map. Units of the fan-shaped deposit are as follows: ridged facies (R & RK), smooth facies (S), knobby facies (K), and flow-like features (L). Some unit boundaries have been re-defined using new data (see Figure 2 for updated smooth facies map).

Knobby Facies: The knobby or hummocky facies consists of sub-km scale knobs and valleys that are subrounded to elongated downslope in places [7]. The density of the knobby facies varies within the Pavonis fan-shaped deposit, with the highest concentrations in the northeastern and western regions of the deposit (Figure 1). The knobby facies appears to superpose underlying features including the ridged facies and flow-like features. We interpret the knobby facies as sublimation till derived from *in situ* down-wasting of ash-rich glacier ice [7, 8].

***Smooth Facies*:** The smooth terrain at Pavonis covers an area of approximately 12,000 km^2 and is morphologically unique when compared to the Arsia smooth facies. There are four isolated regions of the smooth facies within the Pavonis deposit; the largest of which is a continuous deposit north of the shield extending into the central regions of the fan-shaped deposit (Figures 1 & 2). The smooth deposits are characterized by broad, gentle slopes with very few impact craters and vast dune fields covering the surface. These dunes are generally 5-15 m high, 30-100 m wide, with a spacing of around 50-100 m. The smooth facies has the lowest albedo values of any features within the fan-shaped deposit, while within the smooth facies, thinner areas around the margins have a lower albedo than the thicker, central regions.

The smooth terrain superposes all other facies within the Pavonis fan-shaped deposit. For this reason, it has been suggested that the smooth facies may represent pyroclastic flows erupted from volcanic vents after the emplacement of the ridged and knobby facies [7]. However, MOLA topography reveals that the smooth terrain does not “flow” into regions of low elevation the way such volcanic flows would be expected to behave. Instead, the smooth facies consists of convex-outward lobes with central elevations of over 700 m higher than the contact with surrounding terrain (Figure 3).

There are two smaller isolated outliers of the smooth terrain approximately 60 and 80 km west of the main deposit. The larger of the two outliers is over 60 km long and 20 km across at its widest point with a maximum elevation of around 400 m above the surrounding plains. The smaller outlier is approximately 25 km long and 10 km across with a maximum elevation of around 350 m above the surroundings. In addition, a small region of the smooth facies is present on the opposite side of a topographic barrier adjacent to the main smooth facies deposit (Figure 2). The presence of these outliers suggests that the smooth facies is probably not the result of one large volcanic event from a single source; no vents have been seen anywhere near the two outliers, which are over 150 km from the base of the shield. It is also unlikely that any pyroclastic flow would be viscous enough to achieve the observed elevations.

Instead, it appears that these outliers may be remnants of a larger, continuous smooth terrain deposit that existed late in the evolution of the Pavonis fan-shaped deposit. The western margin of the main smooth deposit has a much steeper slope (~3-4˚) than any of the other margins which gently slope (<1˚) into the surrounding terrain. This steeper region of the main smooth facies deposit has dimensions of approximately 60-70 km long with a relief of nearly 500 m and elevation of around 3.6-3.7 km above mars datum. The larger, inner outlier has a length of around 60 km and an elevation of approximately 3.6 km above mars datum (Figure 3). This consistency in elevation and length between the two sections of smooth terrain, along with their proximity and apparent alignment, suggests that they may have been part of a larger smooth deposit in recent Martian history.

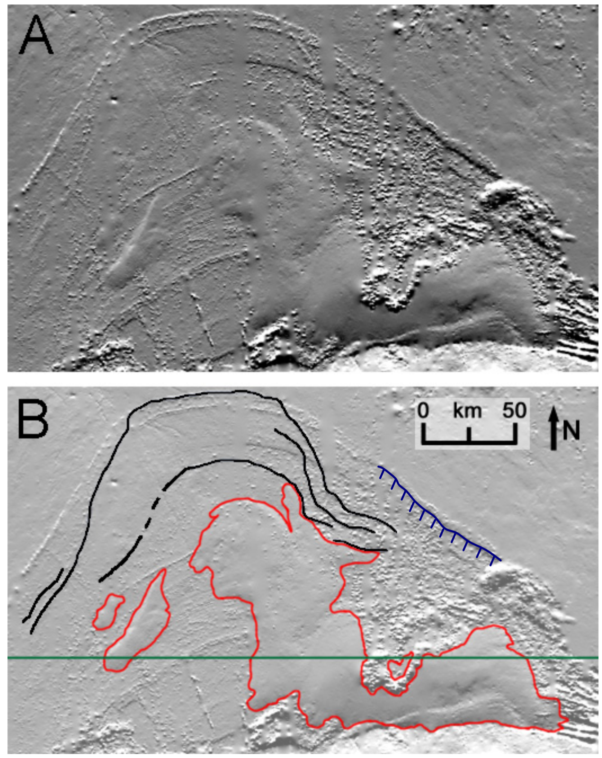

Figure 2: A) MOLA shaded relief map of northern fan-shaped deposit with false illumination from the North; B) Sketch map outlining smooth facies (red) and additional set of ridges (black) and eastern scarp (blue). Green line is location of MOLA profile in Figure 3.

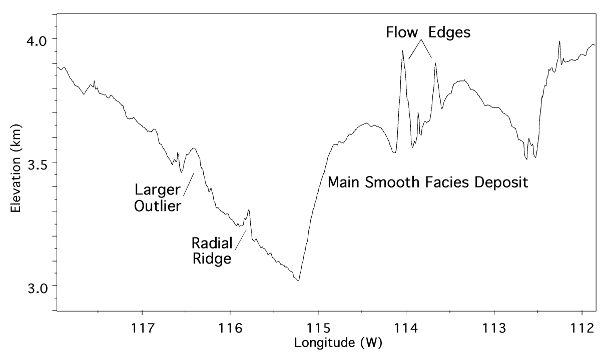

Figure 3: MOLA profile at 4.83˚ N (see green line in Figure 2 for context) across the fan-shaped deposit (118˚-112˚ W) showing the topography of the smooth facies. Vertical exaggeration is 300x.

We interpret the smooth terrain to be dust-covered residual ice from the last major Pavonis Mons cold-based glacier. At its furthest extent, this ice sheet would have covered a significant portion of the fan-shaped deposit. Within the glacier, regions with thick debris cover would be preserved, while surrounding regions with thinner insulation would sublimate relatively rapidly. Thus, the presence of the four isolated regions of smooth terrain under current climate conditions indicates that they are most likely insulated by a significant debris cover, possibly a few meters thick.

Evidence for Multiple Phases: An additional series of ridges appear to superpose all other units of the Pavonis fan-shaped deposit, including the ridged facies (Figure 2) [8]. These ridges are not concentric to the margins of the fan-shaped deposit and cannot be classified as members of the outer ridged facies. Instead, they appear to be concentric to the current margins of the smooth facies, and are most pronounced to the north of the smooth facies, suggesting that the two are related. The longest of these ridges can be traced for over 300 km and reaches heights of over 80 m above the surrounding terrain. The outermost of these ridges actually extends beyond the ridged facies along the northern fan-shaped deposit boundary onto the surrounding Tharsis plains. We interpret these additional ridges to be drop moraines, deposited during retreat of a larger smooth facies ice sheet. This additional set of ridges indicates that a minimum of two phases of moraine deposition occurred, specifically during the formation of the ridged facies and later the additional smooth facies ridges.

Flow-like Features: An area of several unique flow-like features exists in the western regions of the fan-shaped deposit (Figure 1) which have been previously classified as "lobate flow features" [5]. These features are morphologically different from subaerial lava flows at higher elevations on the flanks of Pavonis and also from the Tharsis Plains flows beyond the fan-shaped deposit to the west. They consist of elevated plateaus with leveed edges and steep walls, some with relief of over 500 m. High-resolution MOC images and THEMIS Day IR images across these flow-like features reveal that they are superposed in places by the knobby facies, which continues uninterrupted onto the surrounding terrain. Based on Viking Orbiter data, Scott et al [6] identify these features as elongate, sinuous ridges and suggest that they may be eskers formed by deposition of sedimentary material beneath or within a wasting ice sheet. They suggest an alternative explanation that these features may be unique lava flows originating from troughs on the lower western flank of Pavonis [5, 6]. MOLA topography data have revealed that these features are most likely lava flows; however, their steep scarps and leveed edges are not characteristic of typical martian lava flows. A possible explanation for these features involves subglacial eruptions [9]. This would be consistent with the observation that the knobby (hummocky) facies appears to superpose some of the flows without interruption. Subglacial flows of this volume would be expected to produce a significant amount of heat and meltwater. We have not observed any features indicative of large releases of subglacial water reservoirs similar to terrestrial jokulhlaups; however such features may not be associated with cold-based glaciers.

Radial Ridges: Several linear ridges are present in the central regions of the fan-shaped deposits. These ridges are radial to the base of the shield and have dimensions of approximately 100-200 m high**,** 1 km wide, and 30-60 km long**.** One of these ridges continues beneath the smooth terrain and another is superposed by the western flow-like features. They have previously been interpreted as levees at the margins of a broad flow channel [10] and eskers [6]. Analysis of high-resolution MOC images and THEMIS Day IR images suggests that these features may be radial dikes, which possibly erupted in a subglacial environment [9].

Eastern Scarp: Additional evidence in support of the glacial hypothesis is seen where the Pavonis fan-shaped deposit is bounded to the east by flows (Figures 1 & 2). A large scarp exists in these regions where the fan-shaped deposit is 200-250 m lower than the adjacent lava plains [8]. It appears that these lava flows were deflected from flowing toward lower topographic areas and instead continue for over 100 km to the north-northwest. This type of behavior would not be physically possibly unless some obstacle was present to deflect the flows. The most likely candidate would be a large ice sheet with a relief of at least 250 m that existed at the time of lava emplacement.

Observations of Viking orbiter images reveal that the knobby facies actually extends an additional 5-10 km beyond the scarp onto the lava plains. We have developed the following model to explain the scarp formation and associated features: 1) a large cold-based glacier existed with outer margins at the current location of the scarp, 2) lava flows from Pavonis flank eruptions bank up against the ice sheet, cool and solidify, 3) due to net accumulation, the cold-based glacier undergoes an additional 5-10 km of advance onto the newly formed lava plains, followed by 4) subsequent sublimation, down-wasting and deposition of debris as the knobby facies.

Cold-Based Glacial Model: Current temperatures on Mars are such that glacial activity is more likely to be similar to terrestrial polar glaciers (cold-based) as opposed to wet-based glaciers typical of more temperate latitudes [7]. The fan-shaped deposit at Pavonis Mons provides significant evidence in support of a cold-based glacial model. The ridged facies bears a striking similarity to terrestrial drop moraines associated with recession and deposition by terrestrial cold-based glaciers such as the Antarctic Dry Valleys [7]. In addition, the knobby facies appears to be debris deposited during sublimation and down-wasting of glacial ice, similar to sublimation tills observed in the Antarctic Dry Valleys [7]. Finally, based on MOLA topography, MOC images and THEMIS day IR images, we believe that the smooth facies consists of debris-covered residual ice from the most recent phase of glaciation at Pavonis.

Origin of Proposed Glacier: The obliquity of Mars varies chaotically between 0° and 60° [11]. The proposed ice sheet(s) could have formed during periods of high obliquity where equatorial regions receive less solar insulation than the poles and can become cold traps [12]. Under these conditions, significant evaporative loss of any volatiles at the poles would occur [12]. These evaporative losses would increase the atmospheric volatile content, eventually resulting in precipitation at cold traps. Thus, "at high obliquities (>35°), significant amounts of water could be transported equatorward to be deposited as ice at low latitudes" [13]. It is possible that during periods of high obliquity, "a localized icecap could have been enhanced by orographic effects on wind circulation" [13]. This process involves the same principle as a terrestrial rain shadow where an air mass with high moisture content is forced upward by the topography of the surface below. As the air mass moves upward, the moisture is precipitated out on the windward side of the obstacle, leaving the lee side in a "rain shadow". The fact that all three of the Tharsis Montes fan-shaped deposits are observed on the west-northwestern side of each shield would indicate that regional winds out of the west-northwest existed at the time of deposition. Under current climactic conditions, large water ice clouds are observed on the west-northwestern side of each of the Tharsis Montes in daily MOC wide angle mosaics, suggesting that the rain shadow hypothesis is viable (Figure 4). The more northerly trend of the Pavonis fan-shaped deposit (N35°W at Pavonis vs. N65°W at Arsia and N85°W at Ascreus [7]) may have been influenced by a broad topographic rise to the west of Pavonis Mons deflecting the glacier to the north.

If these cold-based glaciers formed during times of active volcanism, their composition would be influenced by erupted volatiles and ash [4]. The proposed ice sheets undoubtedly contained a significant amount of englacial and supraglacial debris. This debris would be deposited as the ice sublimated and retreated, forming the features of the fan-shaped deposits.

References: [1] K Edgett, LPSC 20, 256, 1989; [2] Carr et al, JGR, 82, 3985, 1977; [3] R Williams, GSA 10, 517, 1978; [4] B Lucchitta, Icarus, 45, 264, 1981; [5] J Zimbelman and K Edgett, LPSC 22, 31, 1992; [6] Scott et al, USGS Geol. Map, 1998; [7] J Head and D Marchant, In Press, Geology, 2003; [8] D Shean and J Head, LPSC 34, 2003; [9] L Wilson and J Head, Geol. Soc. SP202, 2002; [10] C Hodges and H Moore, USGS Prof. Paper 1534, 1994; [11] J Laskar and P Robutel, Nature, 362, 608, 1993; [12] B Jakosky and M Carr, Nature, 315, 559, 1985; [13] M Carr, Water on Mars, 1996.

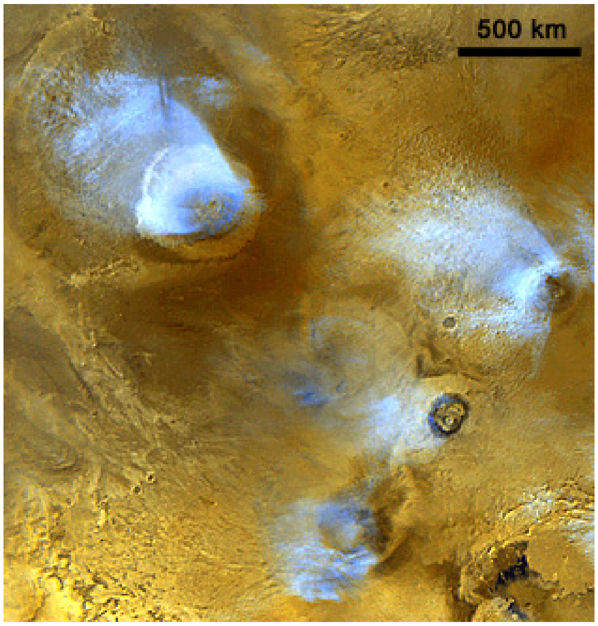

Figure 4: Mars Global Surveyor daily weather image mosaic taken April 1999 during a normal Northern summer day. Bluish-white water ice clouds are present to the north-northwest of each of the Tharsis Montes (Image credit NASA/JPL/MSSS #PIA02066).