TROPICAL MOUNTAIN GLACIERS ON MARS: EVIDENCE FOR AMAZONAIN CLIMATE CHANGE:
James W. Head[1], David E. Shean[1], Sarah Milkovich[1] and David Marchant[2], [1]Dept. Geol. Sci, Brown Univ., Providence, RI 02912 USA, [2]Dept., Earth Sciences, Boston Univ., Boston, MA 02215 USA, james_head@brown.edu

Introduction and background: Polar deposits on Mars represent one of the most significant current volatile reservoirs on the planet and these, together with high-latitude surface and near-surface ground ice, the global cryosphere, possible groundwater, and small amounts of atmospheric water vapor, represent components of the hydrological cycle. Recent Odyssey data have been interpreted to signify the presence of significant amounts of near-surface ice at mid-to high latitudes in both hemispheres [1]. These deposits, together with other topography and morphology data, have been interpreted to mean that volatile-rich deposits have been emplaced from about 30° north and south latitude to the poles during obliquity excursions on the order of <35° [2], perhaps relatively recently, in agreement with predictions from climate models [3].

In this contribution, we outline evidence for the accumulation of ice deposits below 30° north and south latitude during the Amazonian Period. These near-equatorial ice accumulations take the form of tropical glacier deposits that extended outward from the flanks of the Tharsis Montes and Olympus Mons (Figure 1).

Interpretation of Glacial Landforms on Mars: Recent terrestrial studies as well as analysis of landforms on Mars have led to a new understanding of cold-based glacial landforms [e.g., 4]. Although cold-based glaciers do not erode their underlying substrates appreciably, they do deposit characteristic landforms. The material within these landforms originates from supraglacial debris, commonly rockfall and/or volcanic ejecta that falls onto the glacier surface. These rockfall and volcanic particles flow passively through the ice toward glacier margins. During deposition, 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.

The term *drop moraine* is used here to describe ridges that form as supra- and englacial particles are dropped passively at the margins of cold-based glaciers. In the Dry Valleys, such moraines may be cored by glacier ice, owing to the insulating effect of the debris on the underlying glacier. 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.

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 a few Ma. Differential flow of underlying glacier ice may result in distinct surface lobes of sublimation till

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. 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. Spoon-shaped hollows that commonly form at the head of many terrestrial rock glaciers likely arise due to excess sublimation in areas with incomplete debris cover as opposed to preservation by the more extensive tills down valley.

Three shield volcanoes, collectively known as the Tharsis Montes, cap the broad Tharsis Rise, a huge center of volcanism and tectonism spanning almost the entire history of Mars. Olympus Mons is located on the flank of the rise (Figure 1). Each of these volcanoes, although largely constructed of effusive and explosive volcanic deposits, contains a distinctive and unusual lobe, or fan-shaped deposit on their west-northwestern flank. These deposits consist of three facies 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 [see review in 5].

New Mars Orbiter Laser Altimeter (MOLA) altimetry and Mars Orbiter Camera (MOC) images from the Mars Global Surveyor spacecraft have permitted us to characterize the fan-shaped deposits in much more detail. On the basis of present surface temperatures on Mars and those of the recent past, any mountain glaciers would likely 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.

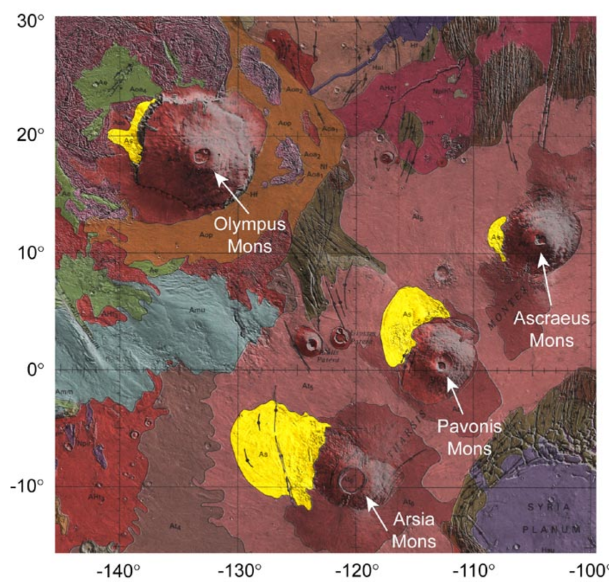

Figure 1. Geologic map of Mars showing the fan-shaped deposits (yellow, unit As) associated with the northwest flanks of the Tharsis Montes and Olympus Mons [8].

Arsia Mons: At Arsia Mons, an outer ridged facies that consists of multiple laterally extensive, arcuate and parallel ridges resting without disturbance on both well-preserved lava flows and an impact crater, is interpreted to be a series of drop moraines formed at the margin of an ablating and predominantly receding cold-based glacier. A knobby facies that consists of equidimensional knobs, each up to several kilometers in diameter, is present inward of the ridges; this facies is interpreted as sublimation till derived from *in situ* downwasting of ash-rich glacier ice. A third facies comprising distinctive convex-outward lobes with concentric parallel ridges and aspect ratios elongated downslope likely represents rock-glacier deposits, some of which may still be underlain by a core of glacier ice. Taken together, these surficial deposits show that the western flank of Arsia Mons was occupied by an extensive mountain glacial system accumulating on and emerging from the upper slopes of the volcano and spreading downslope to form a piedmont-like fan occupying in excess of 180,000 km^2. 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.

Pavonis Mons: The Pavonis fan-shaped deposit (Figure 1) extends approximately 250 km northwest of the shield base [6]. 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. The ridged facies consists of a series of hundreds of concentric, parallel ridges around the distal margins of the deposit. 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 geographic distribution of the ridged facies is unique to Pavonis. We interpret these ridges as drop moraines formed at the margins of a retreating cold-based glacier. A knobby or hummocky facies, that lies both inward and outward of the ridged facies, consists of sub-km scale knobs and depressions that are subrounded to elongated downslope in places. The knobby facies appears to superpose underlying features including the ridged facies, and we interpret it to be a sublimation till derived from *in situ* down-wasting of ash-rich glacier ice. There are four isolated regions of the smooth facies within the Pavonis deposit, the largest extends into the central regions of the fan-shaped deposit.

Additional evidence in support of the glacial hypothesis is seen where the Pavonis fan-shaped deposit is bounded to the east by lava flows. A large scarp exists in these regions where the fan-shaped deposit is 200-250 m lower than the adjacent Tharsis plains. 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. The most likely explanation is that a large ice sheet with a relief of at least 250 m blocked westward flow at the time of lava emplacement.

An area of several, high relief, unique flow-like features exists in the western regions of the fan-shaped deposit. These features are morphologically different from subaerial lava flows at higher elevations on the flanks of Pavonis outside the fan-shaped deposit and also from flows on the Tharsis plains 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. Also present in the central regions of the fan-shaped deposit are several linear ridges. 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**.** Analysis of high-resolution MOC images and THEMIS Day IR images suggests that these features may be flows and radial dikes, which erupted in a subglacial environment.

Ascraeus Mons: Ascraeus Mons has the smallest fan-shaped deposit of the three Tharsis Montes, which extends approximately 90 km from the base of the shield [7] and covers an area of around 30,000 km^2. The strong westerly trend and small size of the deposit confine the accumulation zone for the glacier on the lower western flanks of Ascraeus Mons. Within the fan-shaped deposit, we see a well-defined ridged facies around the outer margins of the deposit as well as an area of the knobby facies in the central regions. Several flow-like features are also present, similar to those observed at Pavonis. They appear to emanate from a series of fractures to the southwest of the fan-shaped deposit. These flows form a large, 300 m high scarp that is roughly concentric to the outer margin of the Ascraeus fan-shaped deposit, suggesting that they were emplaced at a time when an ice sheet was still present at Ascraeus. The most obvious dissimilarity between the Ascraeus deposit and those at Arsia and Pavonis is the absence of the smooth facies. The lack of a smooth facies at Ascraeus may indicate that it was never present or that underlying volatiles have completely sublimated away due to recent climatic conditions.

Olympus Mons: Extending from the base of the Olympus Mons scarp is a unit consisting of several facies, the most extensive of which are fan-shaped deposits including multiple lobate deposits extending up to 90 km from the base of the scarp. Individual lobes are characterized by regular, arcuate, subparallel ridges up to 60 km long. Many depressions are found in this unit; several are circular and are interpreted as small impact craters while others are irregularly shaped. Depressions tend to be hundreds of meters wide and thousands of meters long with depths on the order of tens of m. One lobe is approximately 700 m high and concave in topographic profile. The margins of the lobes are marked by linear ridges hundreds to thousands of meters long and tens of meters high. This unit is interpreted as the remnants of debris-covered glaciers extending from the basal escarpment. The ridges are interpreted to be moraines. Cross-cutting relations imply several episodes of advance and retreat.

Five lobes on Olympus Mons can be traced back to cirque-like hollows in the basal escarpment. The steep scarps at the heads of these erosional hollows rise approximately 4 km above the fan-shaped deposits, and may have served as the accumulation regions. The characteristics of the Olympus Mons fan-shaped deposits are similar in scale and morphology to features within the Tharsis Montes deposits interpreted to be rock glaciers to rock glaciers in the Antarctic Dry Valleys. The ridges at the outer margins of the deposit lobes are interpreted to be distal moraines and the concentric ridges to be drift ridges typical of Antarctic Dry Valley and may other rock glaciers.

Summary and Conclusions: During the Amazonian, significant climate changes created conditions that permitted accumulation of ice deposits in excess of several hundreds of meters thickness, their spreading away from the base of the volcanoes, and their retreat and readvance. Deposits range up to 180,000 km^2 in area and must have persisted for significant periods of time. These deposits provide evidence for the existence of tropical mountain glaciers and are testimony to the possibility of radical climate changes that might have accompanied orbital parameter perturbations such as obliquity excursions in excess of 45^o.

References: 1) W. Feldman et al, *Science*, 297, 75-78, 2002; 2) J. Mustard et al., Mars 6, #3250, 2003; 3) M. Richardson and J. Wilson, *JGR*, 107, 7.1-7.28, 2002; 4) J. Head and D. Marchant, Mars 6, #3087, 2003; 5) J. Head and D. Marchant, *Geology*, 31, 7, 2003; 6) D. Shean and J. Head, Mars 6, #3036, 2003; 7) J. Zimbelman and K. Edgett, LPSC 22, 31, 1992; 8) D. Scott and K. Tanaka, USGS Map #I-1802-A, 1986.