Thursday, October 16, 2003
Morning Session II
RECENT CLIMATE CHANGE ON MARS: GEOLOGIC EVIDENCE
10:30 a.m. Victoria Room

Mustard J. F. * Head J. W. Kreslavsky M. A. Milliken R. E. Marchant D. R.
Geological Observations, Climate Modeling, and Ice Stability: Evidence for Recent Martian Ice Ages **[#8055]**

Russell P. S. * Head J. W. Hecht M. H.
Volatile-rich Crater Interior Deposits in the Polar Regions of Mars: Evidence for Ice Cap Advance and Retreat **[#8086]**

Kargel J. S. * Molnia B. Tanaka K. L.
Martian Polar Ice Sheets and Mid-Latitude Debris-rich Glaciers, and Terrestrial Analogs **[#8112]**

Hartmann W. K. *
Upper Latitude Ice Flow, Gullies, and Long-Term Glacial History **[#8110]**

Head J. W. * Shean D. E. Milkovich S. Marchant D.
Tropical Mountain Glaciers on Mars: Evidence for Amazonian Climate Change **[#8105]**

GENERAL DISCUSSION

12:00 – 1:30 p.m. LUNCH

GEOLOGICAL OBSERVATIONS, CLIMATE MODELING, AND ICE STABILITY: EVIDENCE FOR RECENT MARTIAN ICE AGES

J. F. Mustard[1], J. W. Head[1], M. A. Kreslavsky[1,2], R. E. Milliken[1] and D. R. Marchant[3], [1]Department of Geological Sciences, Brown University, Providence RI 02912 USA, John_Mustard@brown.edu, [2]Astronomical Institute, Kharkov National University, Kharkov, Ukraine, [3]Department of Earth Sciences, Boston University, Boston MA 02215 USA.

Introduction and Summary: Recent exploration of Mars has revealed abundant water ice in near-surface deposits of the mid-to high latitudes in both hemispheres. Here we show evidence that these near-surface, water-ice rich units represent a mixture of ice and dust that is layered, meters thick, and latitude dependent. These units were formed during a geologically recent major martian ice age, and were emplaced in response to the changing stability of water ice and dust on the surface during variations in orbital parameters. Evidence for these units include a smoothing of topography at subkilometer baselines from about 30° north and south latitudes to the poles, a distinctive dissected texture in MOC images in the +/-30°-60° latitude band, latitude-dependent sets of topographic characteristics and morphologic features (e.g., polygons, 'basketball' texture, gullies, viscous flow features), and hydrogen concentrations consistent with the presence of abundant ice at shallow depths above 60° latitude. The most equatorward extent of these ice-rich deposits was emplaced during the last major martian ice age between 0.4 and 2 Myrs, down to latitudes of 30°. Mars is currently in an "interglacial" period and the ice-rich deposits between 30-60° are presently undergoing reworking, degradation and retreat in response to the current stability relations of near-surface ice. Unlike Earth, martian ice ages are characterized by warmer climates in the polar regions and the enhanced role of atmospheric ice and dust transport and deposition to produce widespread and relatively evenly distributed smooth deposits at mid-latitudes during orbital extremes.

Geological Observations: A number of geological observations made with new data from the Mars Global Surveyor and Mars Odyssey missions show features that are latitude dependent. These build on the latitude dependent features observed with Viking and Mariner data [1, 2, 3]. Kreslavsky and Head [4, 5] investigated the roughness and concavity (Figure 1) of the martian surface with the full resolution Mars Orbiter Laser Altimeter (MOLA). These analyses showed a pronounced smoothing of the 0.6 km baseline topography beginning around 30° N and S and extending to the polar regions. They also showed that the topography showed a distinct reduction in concavity in the 30-60° N and S latitude bands. They attributed these observations to the presence of a meters thick mantle that was continuous poleward of 60° but discontinuous in the 30-60° latitude bands. Mustard et al [6] mapped the presence-absence of a unique meters-scale morphology in Mars Orbiter Camera (MOC) images. The morphology indicated the presence of a meters-thick surface deposit that was in a state of partial degradation. A survey of 15,000 images revealed that this unique morphology was restricted to the 30-60° latitude bands (Figure 1). They interpreted this to indicate the presence of a formerly ice-cemented dust deposit from which the ice had sublimated and that was now being disaggregated and degraded. Other investigators have noted latitude dependence in the presence of unique morphologies such as viscous flow features, gullies, and periglacial-like morphologies [e.g. 7, 8, 9, 10]

A remarkable result of the Mars Odyssey Gamma Ray Spectrometer (GRS) is the high concentration of hydrogen beneath a thin layer of dry soil in the top two meters of the martian soil at latitudes greater than 60°

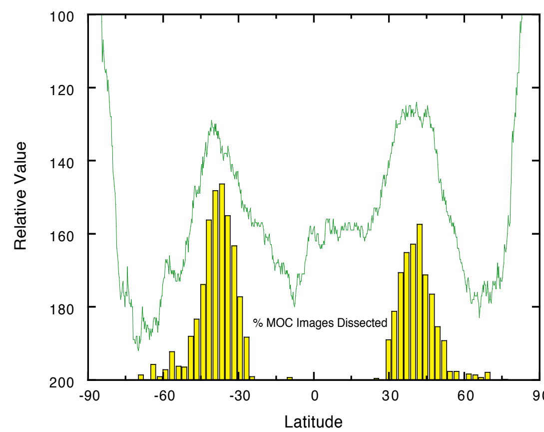


Figure 1: Example of the correspondence among geological observations. The line shows the latitude dependence of topographic concavity while the bars show the precent of MOC images showing dissection. They both show a high correlation in the mid-latitude regions.

N and S [11, 12]. Modeling suggests that the concentration of hydrogen would require 35-50% by mass of water ice, which would correspond to an even greater amount by volume. The present equatorward limit of the these high hydrogen concentrations match extremely well the predicted latitude where ice would be in equilibrium with present-day atmospheric conditions

[13]. Figure 1 shows the latitude distribution of a subset of these features to illustrate their compelling latitude dependence.

Climate Models: The obliquity, eccentricity, and longitude of perihelion of Mars are known to have varied dramatically over the last 10 Myrs [14] and these changes will have important consequences for the martian climate and the distribution of volatiles. Recent modeling of the behavior of the martian climate under different orbital configurations and its effects on the distribution of volatiles [15, 16] predict that at an obliquity of 35°, 10s of meters of water-ice can be sublimated from the poles over an orbital cycle (10s of thousands of years) and redeposited in the mid-latitudes resulting in a meters-thick deposit in these regions. With an obliquity of 45° this process is more vigorous, and in fact deposits of perennial ice are predicted at the equator. Ice deposited by this process is likely to be dust rich.

Orbital Cycles: Ice stability in the near surface of Mars is most strongly controlled by obliquity [13]. When obliquity exceeds approximately 30°, then ice stability moves towards the equator and is stable to within 30° of the equator. Over the past 400 kyrs, the obliquity has remained within a relatively narrow range (22-26°, Figure 2), while eccentricity and precession have varied strongly. If eccentricity and precession controlled the formation of the geologic observations, then we would expect an asymmetric distribution reflecting the most recent conditions. Clearly the geologic observations are almost perfectly symmetric about the equator. Between 400 and 2000 kyrs ago the obliquity regularly exceeded 30°. This would have facilitated the transport of water ice from the poles to the mid-latitudes and be co-deposited with dust. During the brief low obliquity periods between these highs, water ice would sublimate from these deposits. However, surface lags of dust would form, similar to the Fox Permafrost tunnel in Alaska [17] retarding sublimation and preserving aspects of the deposit.

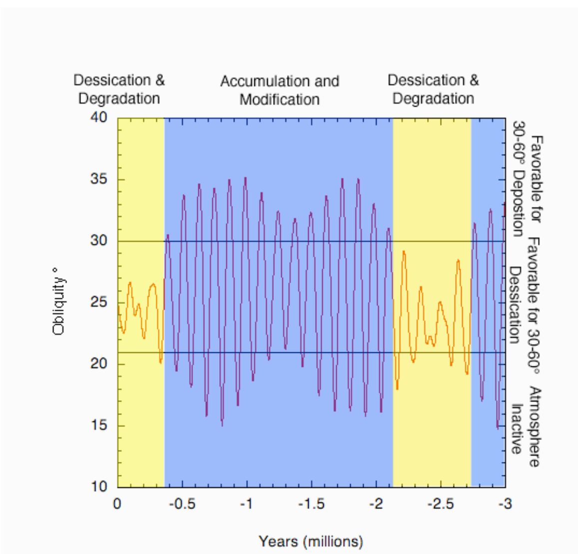


Figure 2. Schematic showing the relationship between obliquity cycles over the last 3 Myrs and deposition-erosion of latitude dependent surface deposits. The blue regions mark martian ice ages, the yellow regions interglacial periods

Martian Ice Ages: The remarkable congruence between geological observations over a range of scales and type with predictions of ice stability over orbital time scales and climate models are strong evidence that the last several million years have witnessed the deposition and reworking, multiple times, of a meters-thick ice-dust deposit in the mid-latitudes of Mars (Figure 2). These are the deposits of the martian ice ages and have significantly affected surface processes in these regions. It is likely that there are remnant deposits beneath surface lags in regions close to the equator.

References:

[1] Squyres, S. W. and M. H. Carr, *Science, 231*, 249-252, 1986; [2] Soderblom et al., *JGR, 78*, 4117-4122, 1973; [3] Squyres, S. W., *Icarus, 34*, 600-613, 1978; [4] Kreslavsky, M. A. and J. W. Head, *JGR, 105*, 26695-26711, 2000; [5] Kreslavsky, M. A. and J. W. Head, *GRL, 29,* 2002; [6] Mustard et al., *Nature, 412*, 411-414, 2001; [7] Malin, M. C. and K. S. Edgett, *JGR, 106*, 23429-23,570, 2001; [8] Carr, M. H., *JGR, 106*, 23,571-23,593, 2001; [9] Milliken et al., *JGR, in press*, 2003; [10] Mangold et al., *LPSC 33*,2002; [9] [11] Boyton W. V., et al., *Science 297*, 81-85, 2002; [12] Feldman W. C., et al., *Science 297*, 75-78, 2002; [13] Mellon, M. and B. Jakosky, *JGR 100*, 11,781-11,799; [14] Laskar J. et al., *Nature 419*, 375-377, 2002. [15] Richardson M. I. and R. J. Wilson, Nature 416, 298-301, 2002. [16] Mischna et al., *JGR 108*, doi:10.1029/2003JE002051, 2003. [17] Johnson, J. J. and R. D., Lorenz, *Geophys. Res. Lett. 27*, 2769-2772 2000;

VOLATILE-RICH CRATER INTERIOR DEPOSITS IN THE POLAR REGIONS OF MARS: EVIDENCE FOR ICE CAP ADVANCE AND RETREAT Patrick S. Russell[1], James W. Head[1], Michael H. Hecht[2], [1]Geology. Dept., Brown Univ., Providence, RI 02912 USA, [2]JPL, Pasadena, CA, USA. Patrick_Russell@Brown.edu.

Introduction: Many craters on Mars are partially filled by distinctive material emplaced by post-impact processes. This crater fill material is an interior mound which is generally separated from the walls of the crater by a trough that may be continuous along the crater circumference (i.e. a ring-shaped trough), or which may only partially contact the crater walls (i.e. a crescent-shaped trough). The fill deposit is frequently offset from the crater center and may be asymmetric in plan view. Populations of such craters include those in the circum-south polar cap region, in Arabia Terra, associated with the Medusae Fossae Formation, and in the northern lowlands proximal to the north polar cap. We focus on those craters in circum-polar regions and assess their relationship to polar cap advance and retreat, especially the possibility that fill material represents remnants of a formerly larger contiguous cap.

Motivated by assessment of the martian hydrological cycle, especially the groundwater system, we have previously examined northern lowlands craters for signs that the impacts may have interacted with the groundwater system [4]. Given the physical and thermal disruption of the ground associated with impact, disruption of the subsurface cryosphere could have allowed effusion of sub-cryosphere confined groundwater into the crater under artesian-like conditions [4,5]. In a globally interconnected hydrosphere-cryosphere system [5], this process would be favored in the northern lowlands, where hydraulic pressure head of groundwater should be greatest [4]. Such a scenario presents an alternative hypothesis for volatile-rich crater fill in northern lowlands craters, but impacts into high-elevation circum-south polar terrain would not be expected to have accessed subsurface water. In addition, the only large craters in the northern lowlands containing significant fill material (e.g., Korolev) are those closest to, but isolated from, the north polar cap [6]. Unless these impacts were very recent, such that the volatile fill had not yet sublimated away [7], this non-random clustering near the north pole suggests that there has been either preferential deposition by polar-like processes in isolated craters, or deposition contiguous to, or part of, a formerly more extensive polar cap [e.g., 3] and subsequent preferential removal of material in intercrater plains. Fill deposits in some craters around the south pole are contiguous with south polar layered material [1], which argues for a similar process of deposition with possible later exhumation or flow into the crater [2].

Volatile-rich deposits have the property of being modifiable by the local stability of the solid volatile, which is governed by local energy balance. Here we test the hypothesis that asymmetries in volatile fill shape, profile, and center-location within a crater result from asymmetries in local energy balance within the crater, due mainly to variation of solar insolation and radiative effects of the crater walls over the crater interior. Model profiles of crater fill are compared with MOLA topographic profiles to assess this hypothesis. If asymmetry in morphology and location of crater fill are consistent with radiative-dominated asymmetries in energy budget within the crater, then 1) the volatile-rich composition of the fill is supported (this process should not be effective at shaping volcanic or sedimentary deposits), and 2) the dominant factor determining the observed shape of volatile-rich crater fill is the local radiative energy budget (and erosive processes such as eolian deflation are secondary or unnecessary).

We also use a geographic and energy model approach to specifically test the idea that material in partially filled craters around the south pole may once have been contiguous to the cap and may have been sustained and modified by radiative processes specific to the crater environment (as opposed to the surrounding plains) as the cap retreated.

Korolev Crater: Korolev crater (~80 km diameter; [6,8]) is superposed on Amazonian mantle material surrounding north polar terrain [1]. While the crater is circular, rim height is not uniform around its circumference. The smooth-surfaced, roughly circular fill deposit within Korolev does not extend completely to the interior walls of the crater, leaving an intervening ring-shaped trough. Relative to the crater's center, the fill deposit is displaced to the north and east, where it reaches closer to and higher up the crater walls. The highest point of the fill deposit is also displaced in the same sense. Based on rim-to-floor depths expected at a fresh, unfilled crater of Korolev's diameter [8,9] the actual deepest point of the crater is not much deeper than the observed elevation. The maximum thickness of the fill mound is then ~1.5 km [8].

Circum-South Polar Craters: There are many craters with fully or partially visible rims within the polar layered terrain of the south polar cap, especially on the half oriented towards 180° (e.g., Fig. 1). Around the fringes of the cap, northern parts of crater rims are fully exposed, while on pole-ward sides crater fill material is still clearly contiguous with polar material (e.g., Fig. 2; [10]). Up to ~ 12° of latitude from the edge of the polar layered terrain are craters with fill material isolated from polar material (e.g., Fig. 3). This isolated fill appears to become less circular and symmetric at greater distances, often located in the northern portions of the crater (e.g., Fig. 4). These materials have been mapped as extensions of polar layered material (Apl; [1]) or as ice and fine dune material possibly derived from polar layered terrain and possibly covering polar layered terrain material deposited in areas of low wind velocity (Ad; [1]).

Based on morphologic and topographic similarity, and in some cases contiguousness, of crater fill with polar layered deposits, we hypothesize that fill material either 1) was deposited preferentially in craters rather than on surrounding plains, or 2) was once present in the plains as well, as part of a larger continuous polar cap, and preferentially remains in the craters today as polar material has retreated from the plains. Fill material in craters partially visible around the edges of the polar layered terrain appears to be maintained by the same conditions as the surrounding, extra-crater polar layered terrain, unless both materials are being deflated and the craters are being exhumed. In some cases there is evidence that physical flow of polar layered material contributed to crater fill deposits [2,10]. Further north, craters not physically connected to the polar layered terrain contain less fill, and this is generally in the form of a circular mound. Yet further north, crater fill is significantly less, occurring only locally within craters. The observed trend of decreasing fill amount with increasing northerly latitude suggests that either deposition and equilibrium-amounts of fill are less at more northern latitudes, or erosive, sublimation, or ablation processes have been more severe at more northern latitudes.

Energy Balance Model: Our approach to determine where and how much modification of an assumed existing water-ice crater-fill occurs is to calculate the main energy input and output pathways for a patch of the surface and assume any excess input energy is available for sublimation. The main processes involved are as follows: 1) solar insolation, including shadowing effects of the crater walls, 2) temperature-dependent reradiation from the surface, including the geometric effects of the crater walls on reducing emittance to the sky, 3) diffusion of heat into or out of the body of ice below the surface, and 4) energy, if any, available for phase change and sublimation of CO_2 and H_2O [11]. By iteratively calculating the energy balance of these processes at different points within the crater, we determine the relative amount of sublimation at each point. The same is done for a point in the plains, outside a crater environment. As an observed proxy for evolution of the modification process, we use characteristic fill morphologies at increasing distance from the south polar cap terrain. If actual fill shape is largely consistent with these modeled processes, then 1) the deposit is likely largely ice-rich, 2) radiative effects likely dominate over wind effects, for example, in the size, location, and shape of such fill, and 3) the retreat (in the plains) of a formerly larger polar cap is supported.

We are interested in timescales less than those of eccentricity and obliquity variations, given the rapid rates of sublimation expected on Mars [7], so we hold orbital parameters constant during each trial. However, the stability of ice changes drastically at different orbital configurations [e.g., 12], so we test several combinations of obliquity and eccentricity. The sensitivity of the model and resulting crater-fill morphology and asymmetry is assessed with respect to physical and geometric parameters such as albedo, emissivity, slope angle, atmospheric scattering (based on [13]), proximity to the crater wall, and crater wall height.

The relative role of incident solar radiation on differently-facing slopes is dramatic. As expected at the high northern latitude of Korolev, south facing slopes receive more total yearly insolation, yet the maximum daily insolation occurs on north-facing slopes due to obliquity effects. With a nominal, non-dust storm, atmospheric optical depth of 0.5, incident insolation is reduced by 10-30% when the sun is more than 10° above the horizon [13]. Albedo can vary by a factor of 4 [11], which directly effects absorbed insolation. The latter two effects affect the total amount of insolation, while the first, and the geometry of the crater, affect the relative distribution of insolation. Asymmetry in insolation is clearly a candidate for being the major control on volatile fill asymmetry, which is supported by observation in a north-south profile across Korolev showing a strong asymmetry in which fill is concentrated to the north, consistent with more yearly energy input from southerly insolation [6].

A nearby high rim, however, will also decrease radiative heat loss by reducing the angle of sky seen by a surface [11]. Due to a thin atmosphere that is ineffective at convecting heat, the sky on Mars is very cold relative to these crater walls. Thus, the greater the visible angle of sky, the more energy can be radiated away, and the more the crater wall fills the field of view, the less the effective emissivity [11]. This concept of effective emissivity is summarized in the following equation: *radiated energy* = :

$$(E\sigma T_{surf}^4 - \sigma T_{sky}^4) * skyfraction + (E\sigma T_{surf}^4 - \sigma T_{cwall}^4) * cwallfraction \quad (1)$$

where E is emissivity of the surface, σ is the Stephan-Boltzman constant, and T is the temperature of the surface, sky, and crater wall, respectively. The hemisphere centered on the normal to the surface is divided into that fraction which is open to the sky and that which is filled, or "blocked" by the crater wall.

Conduction of energy into the subsurface is represented simply by a one-layer slab the thickness of the skin depth. It is assumed that, at each iteration of time, this slab changes temperature based on its heat capacity and the difference between its temperature at the previous time iteration and the temperature at the surface.

The amount of CO_2 deposited and sublimated each season, which we take to be a relatively thin cover over the H_2O ice-rich fill material, is tracked over the interior of the crater based on the latent heat available and assuming the surface temperature never drops below the CO_2 frost point of 148K.

At current orbital configuration, significant energy for sublimation of water ice is not available, thus evolution of deposits may not be currently active. If outlier fill material between ~150° and 240° W longitude was once part of a larger contiguous southern cap, we estimate that on the order of 0.5-2 x 10^6 km^3 of material has since been removed. We are further testing a variety of orbital configurations which will reveal under what conditions, when, and for how long, evolution of ice-rich crater deposits will occur. This will help constrain the relationship of fill material to polar cap material over geological history.

References: [1] Tanaka, K.L., and D.H. Scott (1987) USGS Map I-1802-C. [2] Head, J.W. (2001) *JGR 106*, 10075-10085. [3] Fishbaugh, K.E., and J.W. Head (2000) *JGR 105*, 22455-22486. [4] Russell, P.S., and J.W. Head (2002) *GRL 29*, 17, doi:10.1029/2002GL015178. [5] Clifford, S.M. (1993) *JGR 98,* 10973-11016. [6] Russell, P.S., et al. (2003) *LPSC XXXIV*, #1249. [7] Kreslavsky, M.A., and J.W. Head (2002) *JGR 107*, E12, doi:10.1029/2001JE001831. [8] Garvin, J.B. et al. (2000) *Icarus 144*, 329-352. [9] Pike, R.J. (1988) in *Mercury*, F. Vilas et al., eds., Univ. Arizona Press, 165-273. [10] Pratt, S., and J.W. Head (2002) *LPSC XXXIII*, #1866. [11] Hecht, M.H. (2002) *Icarus 156*, 373-386. [12] Mellon, M.T., and B.M., Jakosky (1995) *JGR 100*, 11781-11799. [13] Pollack, J.B. et al. (1990) *JGR 95*, 1447-1473.

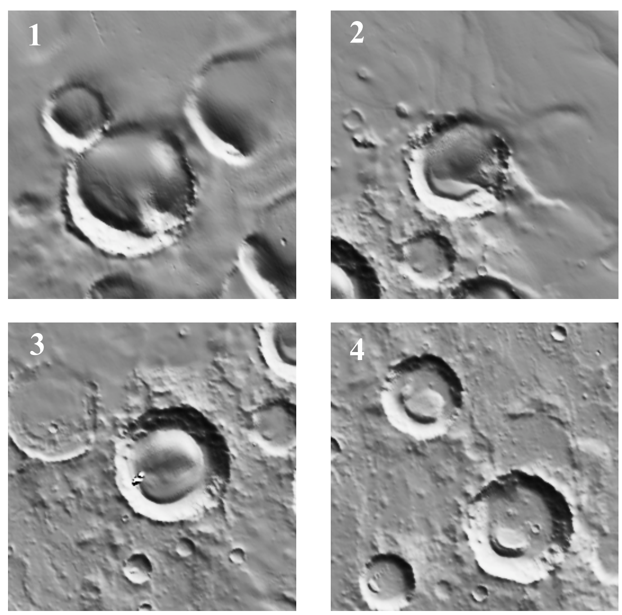


Figure 1. Crater rims visible, or partially visible, through the south polar layered terrain. 75°S, 120°W. All figures at roughly same scale: ~200 km wide. **Figure 2.** Crater mostly exposed, but still half surrounded with south polar layered terrain. Fill material is still contiguous with polar terrain. 80°S, 124°W. **Figure 3.** Crater isolated from south polar layered terrain, with circular fill material. Nearby fringes of polar layered terrain visible at top. 78°S, 126°W. **Figure 4.** Craters with local, isolated, irregularly-shaped fill material. These craters are furthest from the polar layered terrain. 74°S, 131°W.

MARTIAN POLAR ICE SHEETS AND MID-LATITUDE DEBRIS-RICH GLACIERS, AND TERRESTRIAL ANALOGS. J.S. Kargel[1], B. Molnia[2], and K.L. Tanaka[3], [1]U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, U.S.A.; Email: jkargel@usgs.gov; [2]USGS, Email: bmolnia@usgs.gov; [3]USGS, Email: ktanaka@usgs.gov.

Introduction: Glaciers are commonly defined as perennial masses of ice and snow that exhibit morphologic indications of significant flow down-slope under its own weight (under the influence of gravity). This definition does not imply a particular origin or flow mechanism, and in the broadest sense it does not even require that the ice is H_2O. Thus, terrestrial rock glaciers are a type of glacier by this definition, as are Earth's snow-fed alpine glaciers, ice caps, and polar ice sheets; Martian lobate debris aprons, lineated valley deposits of the fretted terrain, and the south polar cap are also glaciers. Martian glaciers apparently include both H_2O-dominated and CO_2-rich icy flows; the ones being rich in CO_2-rich are restricted to the south polar cap. Debris-covered snow-fed glaciers and periglacial rock glaciers provide the closest terrestrial analogs to lobate debris aprons and lineated valley deposits of the fretted terrain.

Martian glacier types and terrestrial analogs: Among Martian glaciers and their Earth analogs, we observe many indications of both brittle and ductile flow behavior. Scarps and troughs in Mars' carbon dioxide-covered south polar cap locally expose intense deformation— buckles, folds, boudins, crevasses, thrust faults and elastic flexural bulges; and in outlying areas of polar layered deposits faults are common. Although there are profound differences between the Martian polar caps and terrestrial polar ice sheets, many of the morphologic characteristics of the Martian south polar cap are similar to characteristics of Earth's ice sheets.

Crevasses, faults, folds, medial moraines, and pressure ridges are commonly expressed on Martian valley and alpine glaciers as deeply etched surface structures whose relief is brought out by differential sublimation. These features are directly comparable to those of terrestrial valley and alpine glaciers. Only one good example comparable to braided glacial outwash systems on Earth has been identified on Mars. Small gullies and debris flows associated with Martian glaciers, like those widely observed for Himalayan debris-covered glaciers, are common. Indications of sublimation are widespread in precisely the geographic locations where sublimating ice is most expected based on Mars climate models.

Terrestrial glaciers are the closest landform analogs of the Martian glaciers, but some structural features of the Martian icy flows are mimicked by structures best known from high-grade metamorphic and plate tectonic systems on Earth. Terrestrial high-grade metamorphic complexes, where deep crustal spreading of hot plastic layered rocks occurred, offer insights relevant to boudins, folds, and faults in the south polar cap (Figs. 1 and 2). Ductile compressive shortening and the lobate forms of major polar flow lobes (Fig. 3) have good analogs in glacial ice sheets; pahoehoe lava flows exhibit some of the same morphologies. Also in the south polar cap we observe elastic plate flexure, where good process analogs include oceanic plate flexure due to the loads of ocean islands and magmatic arcs. In lobate debris aprons of Deuteronilus Mensae, wrinkle-ridges (similar to those of lunar maria and Martian volcanic plains) and plate obduction (Fig. 4) are observed, but more common are surface buckles, flowlines, and medial moraines (Fig. 5) similar to those of Earth's rock glaciers and debris-covered glaciers.

Conclusions and Implications: The implications of these analogs, along with insights drawn from analytical models, are that (1) the Martian cryospheric flows are composed of a flowing, faulting, folding substance; (2) it is a substance capable both of sublimating and melting at conditions near the Martian surface; and (3) the flow features are generally rheologically layered. This layering in the subpolar glaciers is probably due to differential debris/ice contents as well as vertical thermal stratification. In the south polar cap rheological layering is probably due both to thermal stratification (offering many orders of magnitude variation in effective viscosity) and differential amounts of water ice, dry ice, clathrate hydrate, and minor constituents (salts, acids, and inert dust components).

In contrast with the southern perennial CO_2-surfaced cap, the north polar cap and icy deposits around the southern perennial cap have only rare ductile behavior, folding, and other evident indications of a soft, glacier-like rheology.

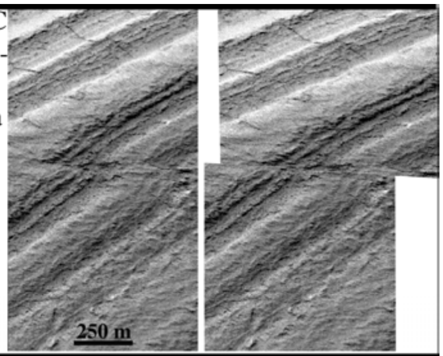
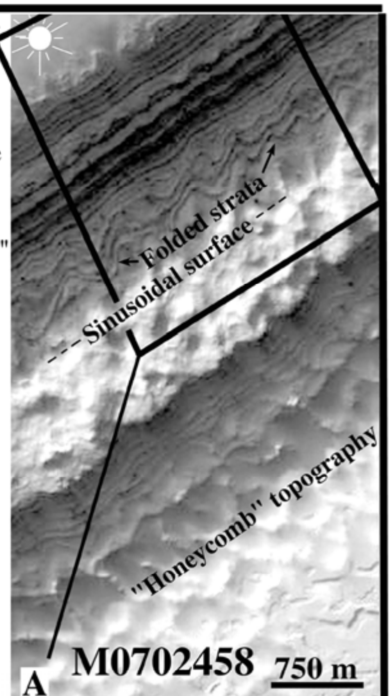


Fig. 1. MOC image M100-3514 shows faulted strata of South Polar Layered Deposits in actual image (left) and recontrsction (right).



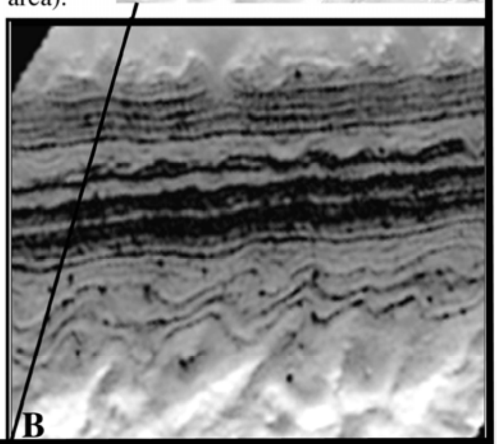
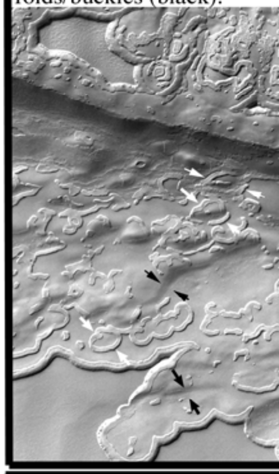


Fig. 2. MOC image M0702458 shows folds exposed in sublimating scarp face of the perennial south polar cap. (A) "Honeycomb" topography may be the eroded expression of boudin structure. (B) Details of folded outcrops (in shaded area) and what may be a folded bedding horizon (in area of direct solar illumination and at the edge of shadow area).

Fig. 3. MOC image m070-3801 shows compressed "swiss" (white arrows) and folds/buckles (black).



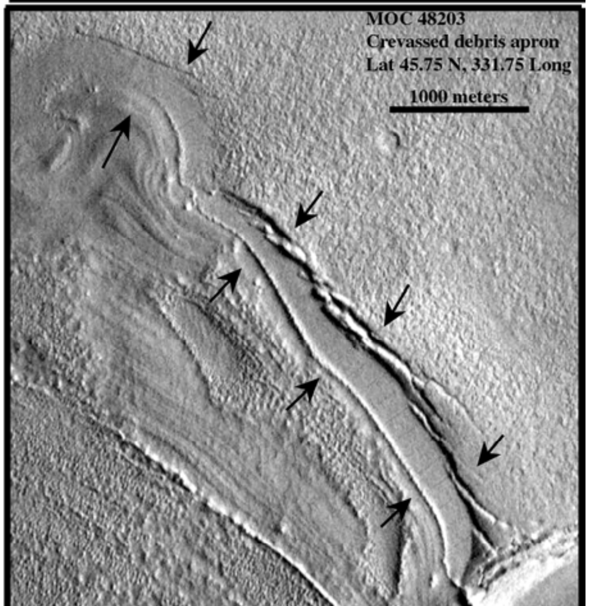


Fig. 4. Mutually obducting lobate debris apron 'plates.'

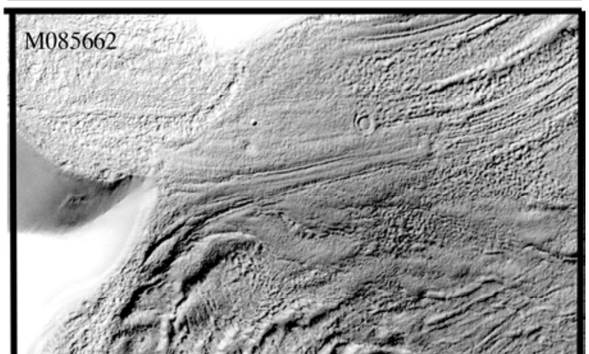


Fig. 5. Medial moraine and flow structure, Coloe Fossae.

UPPER LATITUDE ICE FLOW, GULLIES, AND LONG-TERM GLACIAL HISTORY. W. K. Hartmann, Planetary Science Institute, 620 N. 6th Ave., Tucson, AZ 85705; hartmann@psi.edu

Ice Flow Features: Varied ice-flow-like features have been found in Mars Global Surveyor (MGS) images of moderate to upper latitudes of Mars. Debris aprons give geomorphological suggestions of flow [1], and numerical modeling by Turtle et al. [2] indicates ice flow could deform ice-rich slopes on timescales of 10^3-10^4 y, reaching highly deformed, more steady-state configurations within 10^6 y. Crater counts by Berman [3] and the author (unpublished) suggest that the surface structures at scales of 10-60 m on debris apron surfaces are young, with ages as low as 10^6-10^7 y. Various aspects of terrain softening, observed in upper latitudes, may also involve ice flow [4]. MGS has shown possible ice-flow softening or viscous relaxation of craters as small as a few km [5].

A dramatic tongue shaped feature on a crater wall at ~38° S latitude is likely example of a recent ice flow down the wall [6]. As seen in Fig. 1, the lower crater wall below the tongue is dissected by gullies somewhat different from the classic Malin-Edgett hillside gullies; they may be result of erosion by runoff water from melting of ice in the observed flowing mass, or earlier such masses. Such tongue-like flow features are very rare, but Berman [3] has identified a few similar examples. The south wall of the same crater (unnamed, east of Hellas near Reull Vallis in a region known for debris aprons) also shows flow features, of different morphology. Here, the valleys are filled with chevron-striated deposits that suggest glacial or rock glacial masses.

Relation to Gullies: Hartmann et al. [6] pointed out that the tongue-like apparent flow feature in Figure 1 has a distal crescentic ridge, with a near-concentric, softer arc-like outer ridge further down slope, and that below many Martian hillside gullies similar crescentic ridges can be seen (Fig. 2). Arfstrom [7] gave examples of similar features formed as moraines in terrestrial glaciers, and proposed that these features are moraines formed as glaciers flowed down crater walls after ice mantling. Thus, some gullies may form underneath, or in association with, such ice masses deposited on crater walls. This is consistent with the hypotheses developed by Mustard [8] and Costard et al. [9] invoking deposition of ice-rich dust mantles during long periods of winter cold and dark, during high-obliquity phases of 10^7 y axial tilt cycles.

An explanation for the rarity of beautifully preserved ice flow features such as seen in Figure 1 may be that the flow is fast (as shown by Turtle et al. [2]), and Martian glaciers self-destruct because of high ice losses from the surface of the flowing mass, due to sublimation as the dusty ice mass flows and churns. They may last no more than a few My.

Figure 1. Lobate feature caused by apparent flow down north inner wall of an unnamed crater at 247W 38S. Downhill from the lobate flow, the lower crater wall deposits are dissected by gullying, possibly from runoff associated with ice in previous flows. MOC M18-00897.

UPPER LATITUDE ICE FLOW, GULLIES, AND LONG-TERM GLACIAL HISTORY: W. K. Hartmann

In this view, glaciation and gullying at upper latitudes may come in short-lived episodes launched primarily by ice deposition cycles (and less commonly by local water release, creating ice lenses), and even the moderate upper latitudes of Mars may be viewed geomorphologically as parts of the time-varying polar ice cap.

Long-Term Glacial and Polar History: Tanaka et al. [10] tabulated total areas resurfaced by various processes in different epochs. Using early estimates of Martian chronology based on crater counts, he found that resurfacing by periglacial and fluvial processes declined from high Noachian values. Hartmann and Neukum [11] refined the crater chronology, consistent with ages of Martian igneous meteorites from 170 to 1300 My. Using my own subsequent refinement of those data, I updated the estimates of the durations of the Martian epochs, and computed the rate of resurfacing [(Tanaka total km^2 resurfaced by a given process in a given epoch)/(duration of that epoch)]. The result (Fig. 3) confirms that Noachian/Hesperian periglacial resurfacing rates were an order of magnitude or more the modern rate. Fluvial and volcanic resurfacing also show enhanced Noachian/Hesperian rates relative to the present, indicating that early Mars was a more active and Earth-like environment.

References: [1] Pierce T. L. and Crown (2003) *Icarus, 163,* 46-65. [2] Turtle E. P. et al. (2003) 3rd Intl. Polar Sci. Conf. (this meeting). [3] Berman D. C. (2003) M. S. thesis, U. of AZ, in prep. [4] Squyres S. et al. (1992) In *Mars*, U. AZ Press, Tucson, 523-544. [5] Hartmann W. K. and Esquerdo G. (1999) *Meteor. Planet. Sci., 34,* 167-177. [6] Hartmann W. K. et al. (2003) *Icarus, 162,* 259-277. [7] Arfstrom J. (2003) *LPS XXXIV,* Abstract #1174. [8] Mustard J. F. et al. (2001) *Nature, 412,* 411-413. [9] Costard F. et al. (2003) *Science, 295,* 110-113. [10] Tanaka et al. 1987. *Proc. Lunar Planet Sci Conf. 18th,* 665-678. [11] Hartmann W. K. and Neukum G. (2001) *Space Sci. Rev., 96,* 165-194 with modest updated revisions by W. K. Hartmann, in preparation).

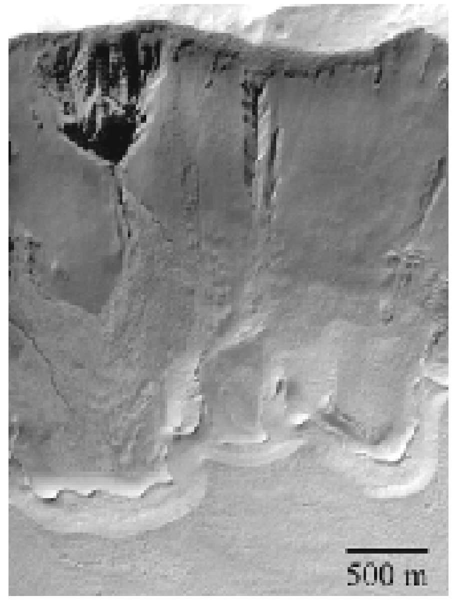


Figure 2. Typical Martian gully system showing sharp arcuate ridge bounded on outside by softer ridges, at the base of the gullied hillside. The arcuate forms, which may be moraines, are similar to those at the foot of the glacier-like mass in image A, suggesting that glacier-like ice rich masses may be associated with gully production. 166W39S MOC M18-00303.

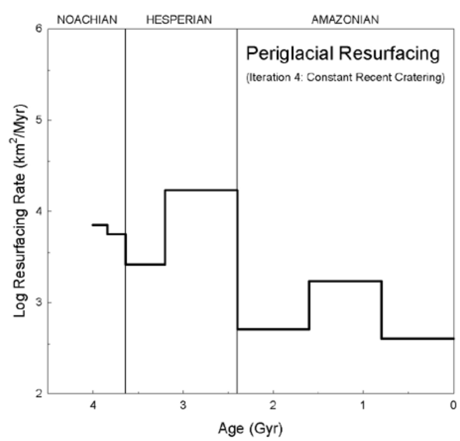


Figure 3. Plot of rate of resurfacing by periglacial processes as a function of time, derived by dividing total area of periglacial resurfacing in each epoch [10] by durations of the epoch [11]. Various timescale by Neukum and by Hartmann agree that Noachian-Hesperian periglacial resurfacing rates were an order of magnitude higher than present values.

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 30º north and south latitude to the poles during obliquity excursions on the order of <35º [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 30º 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.

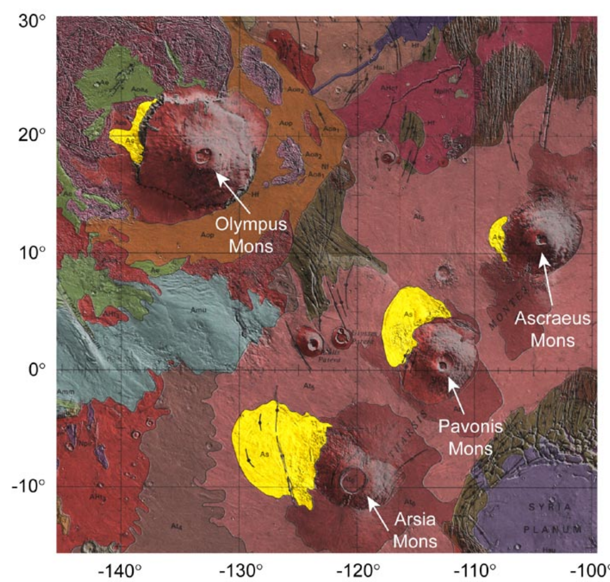


Figure 1. Geologic map of Mars showing the fan-shaped deposits (yellow, unit As) associated with the northwest flanks of the Tharsis Montes and Olympus Mons [8].

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.