Mars: Nature and evolution of young latitude-dependent water-ice-rich mantle

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[1] High-resolution altimetry and imaging have revealed the presence of a meters-thick sedimentary layer at middle to high northern and southern latitudes presently covering at least 23% of the planet. The layer is interpreted to be water-ice-rich, and to undergone degradation recently. Its activity very likely coincided with the last major obliquity excursion a few hundred thousand years ago. The majority of the layer at higher latitudes, however, persisted for a much longer time in the Late Amazonian. Stratigraphic analysis suggests a complex history of successive episodes of deposition and removal. Repeated deposition and removal of the mantles are interpreted to be responsible for the unusual statistical properties of kilometer-scale topography in the transitional mid-latitude zones. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars; 5416 Planetology: Solid Surface Planets: Glaciation; 5464 Planetology: Solid Surface Planets: Remote sensing; 5462 Planetology: Solid Surface Planets: Polar regions

1. Introduction

[2] *Kreslavsky and Head* [2000] used the Mars Orbiter Laser Altimeter (MOLA) data to characterize the kilometer-scale roughness of Mars. They showed that the median absolute value of the differential slope at 0.6 to ~20 km baseline lengths, when plotted as an RGB image (Figure 1) revealed the presence of systematic latitudinal variations of roughness at moderate to high (above 30–50°) latitudes in both the northern and southern hemispheres. Terrains at these high latitudes were shown to be smoother at short baselines, with a characteristic vertical scale of several meters. Superposition of this terrain over older geological units in the roughness data (Figure 1), together with the smoothing and inferred thickness, suggested the presence of a meters-thick mantling layer. Analysis by *Kreslavsky and Head* [2000] supported the interpretation that the mechanism of formation involved deposition of a sedimentary blanket at high latitudes, and they concluded that the several meter thick debris mantle originated through recent climate-related change.

[3] *Mustard et al.* [2001], using MOC images, reported on the presence of a unique young terrain at ~30–60° latitude in both hemispheres that exhibits a specific morphology that they interpreted to be consistent with a material that has been initially cemented and then partially dissected or disaggregated. Their analysis showed that the eroded terrain is concentrated in two latitudinal bands (30–70°N; 25–65°S), with few occurrences either poleward of 60°, or equatorward of 30°. *Mustard et al.* [2001] interpret the material composing the mantle to be cemented dust, and show that where it is removed, the underlying surface appears unaltered by the process of dissection. Of the two mechanisms for cementation, chemical and ground ice, *Mustard et al.* [2001] favor ground ice because: 1) the distribution of the layer is associated with viscous creep features, 2) there is a lack of positive evidence for chemical cement. They interpret the eroded mantle material to be a layer of ice-cemented dust (loess) and soil undergoing dessication, disaggregation and removal. On the basis of these characteristics, they conclude that a process of "airfall deposition concurrent with ice cementation" was responsible for the formation of this layer in the last 0.15 Myr.

[4] *Mellon and Jakosky* [1995] developed models for the latitudinal stability of ground ice under current and past conditions, showing present stability and predicted variations related to changes in orbital parameters, and the resulting formation and removal of ground ice from the upper 2–4 meters of the surface. Currently, ground ice should be stable poleward of ~40°, and the most recent low-latitude excursions from this would have occurred about 0.1 Myr ago, when ice would have been stable down to about 30° latitude.

[5] Thus, on the basis of this model, the results of *Kreslavsky and Head* [2000] and *Mustard et al.* [2001] are interpreted to mean that the unique terrain at 30–60° latitude represents the now-decaying, low-latitude recent expansion of an extensive, and longer term, latitude-dependent near-surface ground-ice-cemented dust or loess layer. Further observations that may be consistent with a recent high-latitude volatile-rich active layer have been cited by *Costard et al.* [2002] (high-latitude gullies from melting of ground ice at higher obliquity), *Siebert and Kargel* [2001] and *Mangold et al.* [2002] (recent melting of ground ice at 50–75° latitude to produce patterned ground), *Cabrol and Grin* [2002] (recent high-latitude mass flows and related features), and *Milliken et al.* [2002] (recent high-latitude viscous flow features).

2. New Observations

[6] Using the full MOLA data set, we have produced new kilometer-scale roughness maps of Mars similar to those presented in *Kreslavsky and Head* [2000] (Figure 1). To produce these maps we calculated the curvature (the second derivative) of MOLA profiles at each of ~6.4×10^8 MOLA footprints using three baseline lengths: the smallest possible (three nearest MOLA footprints, 0.6 km baseline), four times longer (2.4 km baseline) and four more times longer (9.6

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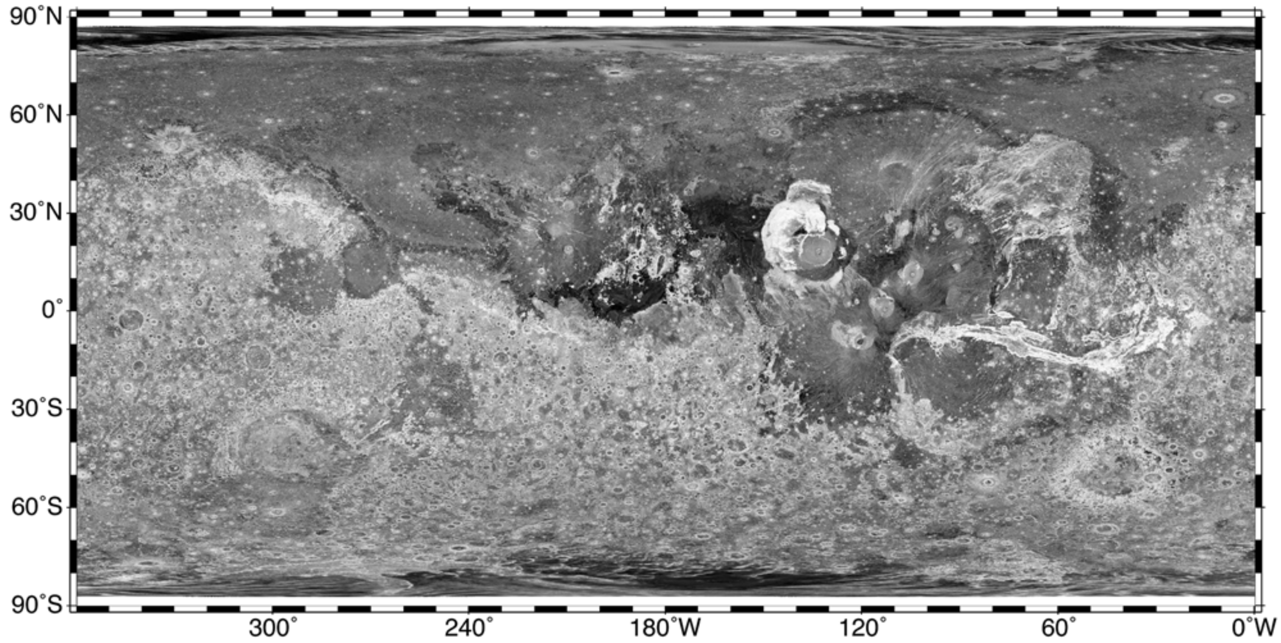

Figure 1. Map of kilometer-scale roughness of Mars (simple cylindrical projection). The map is a composite RGB image, with red, green, and blue channels displaying roughness at baselines of 9.6, 2.4, and 0.6 km, respectively. Brighter shades denote rougher surfaces. See text for further details.

km). All curvature values were binned in the map elements of 8-elements-per-degree simple cylindrical map projection; this gave typically 20–200 data points per map element for each baseline. We used the interquartile width of the curvature-frequency distribution in each bin as a characteristic of roughness at a scale defined by the corresponding baseline length. The resulting maps of roughness at the three scales are shown in Figure 1 as three channels of a color composite image: red (longest baseline), green (intermediate baseline) and blue (shortest baseline). The resulting color map clearly shows the latitudinal trend of roughness that we have documented previously [*Kreslavsky and Head*, 2000]. It is expressed as a prevalence of warmer (orange) shades at high latitudes (southward from ~30–45°S and northward from ~47°N). Relatively warmer shades in the color map denote relatively lower small-scale roughness (lower intensity in the blue channel). In addition to the latitudinal trend, the map (Figure 1) displays pronounced variations of roughness, which correlate with geological units and features (see *Kreslavsky and Head* [2000] for discussion). In the northern hemisphere, the strong roughness contrasts associated with the dichotomy boundary partly mask the latitudinal trend. The trend is better seen in the highlands of the southern hemisphere.

[7] We also mapped the normalized median curvature of the topographic profiles, which characterizes the prevalence of concave (if the median is positive) or convex (if negative) segments of profiles. For example, for a hypothetical terrain formed by smooth knobs or V-shaped troughs, convex profile segments would prevail, while a terrain formed by bowl-shaped craters or sharp ridges would show a prevalence of concave segments. A map of the median curvature at the shortest (0.6 km) baseline (Figure 2) shows a distinctive curvature signature for several geological features and provinces. The systematic difference between equatorial and high-latitude regions can be seen in the map: in the equatorial highlands the median curvature is close to zero or has small positive values, while at high-latitude zones (away from polar caps, dune fields and other regions of unusual topography statistics) concave topography strongly prevails. In the northern hemisphere we cannot exclude that this global tendency is related to the surface dichotomy, while in the southern hemisphere this difference between high- and low-latitude zones occurs within similar highland terrains. The strong prevalence of concave topography at high latitudes is consistent with surface mantles that smoothly fill local lows, while local highs have thinner mantle coverage or protrude through it.

[8] An even more prominent latitudinal effect is the presence of latitudinal zones of the prevalence of convex topography between equatorial and polar regions, exactly in the same areas where the systematic change of the subkil-

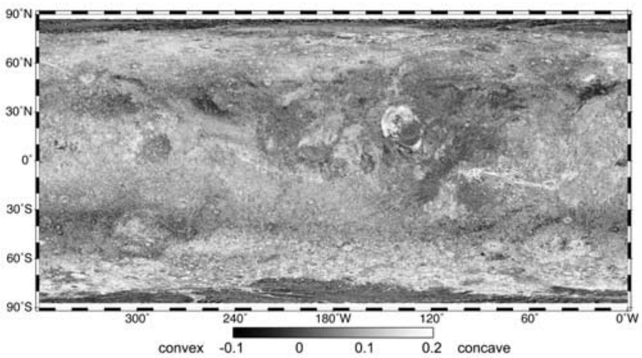

Figure 2. Map of the median curvature of MOLA profiles at 0.6 km baseline normalized by roughness. See text for details.

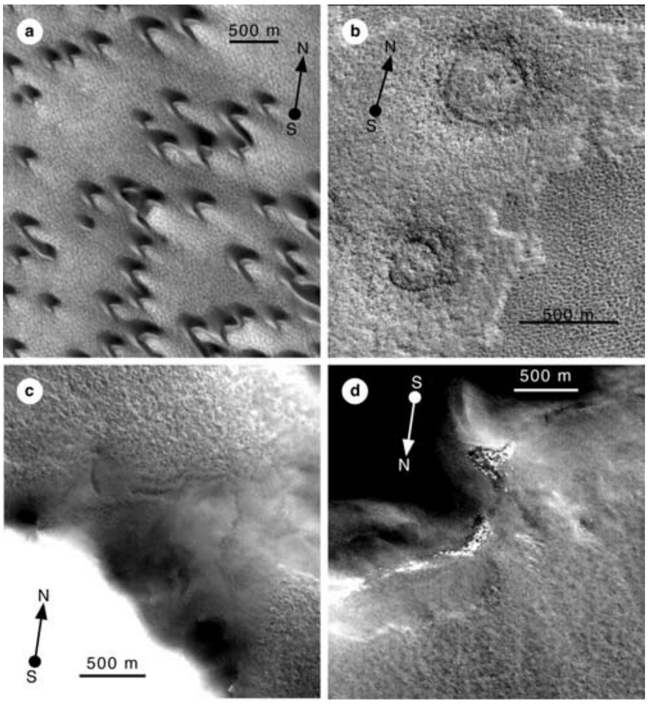

Figure 3. MOC images of the mantles in the northern plains. See text for explanations. Illumination is from lower left. (a) Portion of MOC image M23/01695, 75°N, 51°W. (b) MOC image M02/01316, 69°N, 150°W. (c) The polarward-facing slope of the northern rim of the "young" crater (see text) at 68°N, 267°W. Portion of MOC image M03/04096. The inner southward-faced wall of the crater is saturated white. (d) The polarward-facing slope of the northern rim of the "old" crater (see text) at 71°N, 257°W. Portion of MOC image M00/01895. The inner southward-faced wall of the crater is in shadow.

ometer-scale roughness occurs. Again, in the northern hemisphere these zones interfere with distinctive geological features and provinces, while an obvious concentration of the unusual areas with negative median curvature (dark shades in Figure 2) occurs in the 30–55°N zone. The transitional zone of convex topography prevalence is wider (30–60°S) in Noachis Terra (330–20°W); an analogous statistical signature is observed in Arabia Terra in the northern hemisphere (25–45°N, (300–350°W)). In Terra Cimmeria (140–220°W) the transitional zone is noticeably narrower (37–49°S).

[9] Thus the statistical characteristics of topography in the transitional zone between low-latitude terrains and high-latitude mantles are not simply transitional between these two regions, and show that the surface has its own characteristic features. These zones generally coincide with the zones where *Mustard et al.* [2001] found dissected terrains. These terrains themselves, however, cannot be responsible for the prevalence of convex topography, because the scale of the dissected topographic pattern is much smaller than the scales that can influence the curvature at 0.6 km baseline. In the southern hemisphere, most of the sites with the dissected pattern are found in Terra Cimmeria [*Mustard et al.*, 2001], while the dropdown of the median curvature here is weaker than in Noachis Terra (Figure 2). Small-scale polygons in Utopia Planitia were also interpreted by *Seibert and Kargel* [2001] as desiccation features related to ice-rich mantles. The area of these polygons is within the transitional zone in the northern hemisphere, however the morphology of this terrain is very different from that of dissected terrain discussed by *Mustard et al.* [2001].

[10] The high-latitude zones, especially in the northern plains, are often covered with a specific homogeneous fine-scale hummocky surface texture similar to the surface of a basketball (Figure 3a). In the circumpolar regions, MOC images reveal a number of examples of dark dunes that form and presumably migrate on this mantle (Figure 3a). We studied all MOC images released so far and have not found any sign of the "basketball" pattern being altered by dune migration. This shows that the mantle is rather strong mechanically, which suggests that the mantle is densely packed cemented dust rather than dirty firn.

[11] We showed previously [*Kreslavsky and Head*, 2000] that in the Utopia region, the "basketball" mantle buries the underlying terrain, which is characterized by distinctive pits, scarps, and small-scale polygonal fissures. This observation suggests that the deposition of the "basketball" mantle postdates the desiccation responsible for the formation of the polygonal terrain considered by *Seibert and Kargel* [2001]. We undertook a global examination of all MOC images obtained through the end of 1999 for the latitude range 30–60°N and found that the "basketball" mantle never appears below 45°N, but is common between 45° and 60°N, where the mantle was clearly blanketing underlying terrain. We interpret the "basketball" terrain to be partially desiccated and dissected variations of the layer, in which some of the material has been removed.

[12] The "basketball" mantle is not continuous. Examination of a region where this mantle is being destroyed illustrates its nature and relation to underlying units (Figure 3b). In this area, a ~2–4 meter high (as determined from MOLA profiles) sinuous scarp separates the region of the "basketball" terrain from a more broadly hummocky and variegated terrain in which underlying and exhumed craters and their rim deposits can be seen.

[13] Stratigraphic relationships establish important characteristics of the unit. Over much of the northern high latitudes, the mantle overlies the Late Hesperian Vastitas Borealis Formation (VBF), a unit with a distinctive roughness characteristic [*Kreslavsky and Head*, 2000]. One of the basic characteristics of the VBF is the presence of abundant cratered cones [*Tanaka and Scott*, 1987]. At low latitudes (e.g., in Isidis Basin) these are readily seen, while at higher latitudes they are clearly covered and draped by the mantle.

[14] Impact craters in the northern lowlands have different roughness signatures in high-latitude and low-latitude zones: the craters and their proximal ejecta are systematically smoother at high latitudes and rougher at low latitudes at 0.6 km baseline (Figure 1; craters appear as blue spots on the greenish background of the VBF in the southern parts of the lowlands, while they are orange spots in the central part of the plains). There are two exceptions: high-latitude craters at 73°N 322°W (11 km in diameter) and 68°N 267°W (27 km) are unusually rough (blue in Figure 1). This indicates that these craters were formed

after significant smoothing in the high-latitude zone had occurred. A high resolution image (Figure 3c) shows that the ejecta and rim of this crater are covered with apparently young mantles, rather similar to the mantles on neighboring "old" crater with a regular roughness signature (Figure 3d). This suggests that the most recent mantle in not solely responsible for the latitudinal trend of roughness, and accumulation of high-latitude mantles has occurred for a geologically long time.

[15] On the basis of mapping of its global distribution, the mantle unit (excluding the transitional zone) covers an area of at least 33×10^6 km^2, or at least 23% of the surface of Mars. Using the range of estimates of the thickness of the layer, we estimate that the total volume is of the order of $1 - 2 \times 10^5$ km^3. If the deposit is characterized by a porosity ranging from 10–40%, then this means that the volume of ice could range from 10^4 to 10^5 km^3. This amounts to a global equivalent water layer of 7–70 cm, which is small in comparison to the total present volume of the polar caps.

3. Synthesis and Conclusions

[16] Mapping of the statistical characteristics of the kilometer-scale topography of Mars has revealed circumpolar regions of subdued small-scale topography and unusual transitional zones. The set of morphological observations from high-resolution images is consistent with the interpretation of the latitudinal trend of roughness as the manifestation of unique surface mantle deposits cemented with water ice. The transitional zone is probably related to discontinuous and/or degrading mantles.

[17] Viking 2 lander did not observe any water ice at or near the surface, although the landing site is within the transitional zone and the high-resolution images of the landing site vicinity show a variety of dissected mantles. The global albedo pattern also does not reveal any appreciable correlation with the latitudinal distribution of mantles. The regions of circumpolar mantles, at least, their lower-latitude parts, are characterized by moderate values of thermal inertia [e.g., *Mellon et al.*, 2000], while bare compact deposits with ice-filled pores would have extremely high thermal inertia. All this indicates that the uppermost several centimeters of the surface are likely to be almost free of the cementing ice.

[18] The mantles do not show any similarity in morphology and statistics of topography with polar layered deposits, which are also interpreted to be made of an ice and dust mixture in unknown proportion. This striking dissimilarity indicates that these two types of ice-rich objects have a different origin and probably different ice content.

[19] The latitude-dependent circum-polar mantles have diverse morphology and appear to have a complex stratigraphy, with evidence for a history of at least several (probably, many) successive episodes of deposition and removal. Periods of high obliquity should favor water release from the polar caps and are candidate epochs for the deposition episodes. The uppermost mantles are very young, perhaps associated with the most recent obliquity variations. We show strong evidence that the main set of mantles is much older. The observations are consistent with a suggestion that at the higher latitudes the mantles are rather stable and experience minor modifications during obliquity cycles, while in the transitional zone repeated removal and redeposition of the mantle occurs. The recent findings with gamma ray and neutron spectrometers onboard Mars Odyssey [*Boynton et al.*, 2002] reveal an ice-rich material in the shallow subsurface at the southern high-latitude zone that correspond closely to the distribution of the mantles described here. Orbital remote sensing experiments, such as neutron spectrometry and radar probing, as well as surface exploration, could further map the distribution, thickness, and water content of this layer.

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