EROSIONAL MORPHOLOGIES AND CHARACTERISTICS OF LATITUDE-DEPENDENT SURFACE MANTLES ON MARS. R. E. Milliken and J. F. Mustard, Dept. Geological Sciences, Brown University, Box 1846, Providence, RI 02912 Ralph_Milliken@brown.edu

Introduction: Latitude-dependent layered deposits and terrains on the surface of Mars were first observed in Mariner 9 images [1]. Similar layered deposits were later observed in higher-resolution Viking images, as well as lobate debris aprons, lineated valley fill, concentric crater fill, and terrain softening. The latter group of features were confined to the mid-latitude regions and were attributed to viscous creep of ice-rich material [2,3,4]. In addition to these observations, recent high-resolution images acquired by the Mars Orbiter Camera (MOC) onboard the Mars Global Surveyor (MGS) mission revealed a distinct surface morphology present in the mid-latitude regions [5,6,7].

Mustard et al. [5] described this mantle terrain as a young, smooth, thin (1 - 10 m), layer of an ice-dust mixture. The terrain was identified by its distinctive style of erosion, which results in a pitted or 'dissected' texture. Like the features mentioned above, this dissected mantle terrain (DMT) is only observed within certain latitude bands (±30-60°), and higher latitudes appear to be covered with a thicker, intact mantle [5,8]. MOLA data for these latitude bands show a decrease in surface roughness at short baselines for latitudes greater than ~45° [9, 10] and a decrease in concavity between ~30-60° in both hemispheres that matches the peak occurrence of the DMT [11]. The interpretation of these smooth, high-latitude deposits as ice-rich airfall mantles [9] is supported by the presence of high abundances of near-surface ground ice as determined by Mars Odyssey data [12, 13, 14]. Latitudes greater than ±60° also host many surface features (polygons, cracks, etc.) attributed to periglacial processes, further supporting the presence of ice-rich deposits at these latitudes [15].

These previous observations provide clear evidence for hemispherically symmetrical, layered, latitude-dependent deposits. *Mustard et al.* [5] interpreted the mid-latitude mantle terrain to represent airfall deposition of an ice-dust mixture during the most recent period(s) of high obliquity. The current instability of near-surface ice in the mid-latitudes results in sublimation and removal of the mantle. At higher latitudes, however, near-surface ice is currently stable. The lines of evidence outlined above are proof of the presence of ice-rich deposits within the high-latitudes of Mars. If it is true that the previous extent of these deposits reached the lower mid-latitudes, the current morphology and degradation state of the mantle terrains may give insight to past or current erosional processes, local variability in near-surface ground ice stability, changes in mantle thickness and/or composition, and improved age estimates. Of the 13,000 MOC images we have examined to date, ~1,700 contain the DMT. This work concentrates on re-examining this subset of images in an attempt to characterize the different morphologies, erosional styles, and properties of the observed latitude-dependent surface mantles.

Observations: For simplicity, the latitude-dependent mantle deposits will be spatially classified in the following manner: latitudes less than ~ ±30° do not currently exhibit the mantle terrain and will be classified as "unmantled"; the eroded or dissected terrain described by *Mustard et al.* [5], present between ±30-60°, will be referred to as "dissected mantle terrain" (DMT); the thicker, intact mantle deposits commonly found at latitudes greater than ~ ±60° will be referred to as "mantled". Where present, the mantle terrains are not homogenous at all latitudes. The morphology and erosional styles of the DMT, for instance, is variable with latitude. Though many styles are observed, we have classified three major erosional morphologies of the DMT.

Localized Complete Removal The first erosional morphology will be referred to as "localized complete removal". As the name suggests, this type of erosion is characterized by areas of smooth, intact mantle adjacent to areas where that mantle has been completely removed to reveal a rougher underlying unit (Fig. 1a). It cannot always be determined if this underlying unit is bedrock, and it is clear in some MOC images that the removal of the uppermost layer has revealed a stratigraphically lower mantle layer (Fig. 1a). Unlike the top layer, the underlying mantle layer is highly degraded and cratered in several images This suggests that some of the underlying mantle layers are much older, and may represent periods of deposition prior to the most recent periods of high obliquity.

Areas of the DMT with clear examples of layering are restricted almost entirely to this erosional style and are typically only found between ±30-40° (Fig. 2). The localized complete removal erosion style is most commonly found between ±30-50°, with a peak occurrence near ±30° (Fig. 3a).

Knobby and Wavy Dissection The second erosional style is a surface texture dominated by small bumps, knobs, or ripples. This type of DMT is classified as "knobby and wavy" dissection and is identified by areas of smooth, intact mantle adjacent to areas of incomplete removal of the mantle. Areas covered by the knobby texture (Fig. 1b) and/or wavy texture (Fig. 1c) obscure the substrate and represent an intermediate stage of removal of the mantle terrain.

The knobby texture often grades into series of lineated knobs, which then grades into the wavy texture as latitude increases. Images that show only the wavy texture are uncommon, and most areas of DMT that

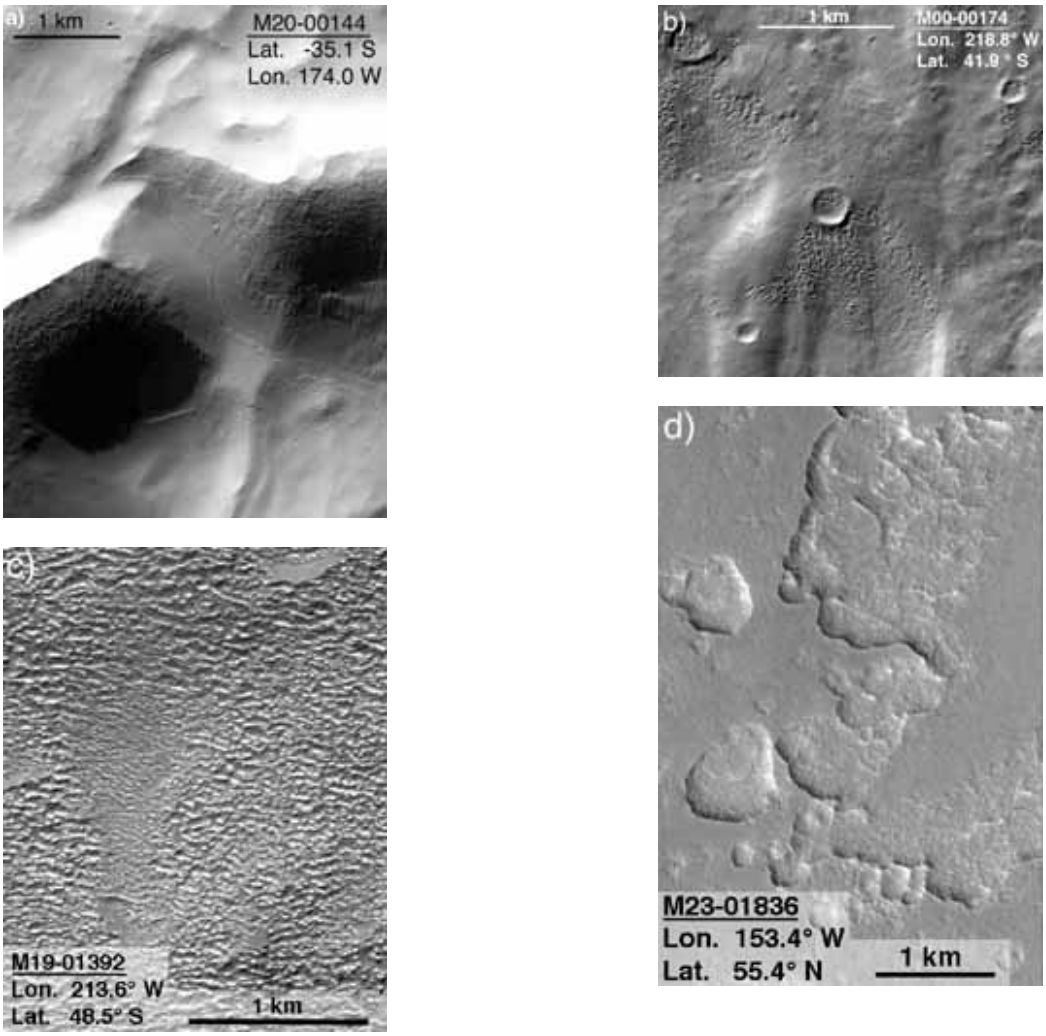

Figure 1. Examples of the major classes of dissected mantle terrain. a) localized complete removal; smooth intact mantle adjacent to areas of complete removal (on shadowed slopes); layers of the mantle are visible on the shaded side of the right-hand slope. b) knobby texture; areas of smooth mantle adjacent to areas of incomplete removal; typically grades intoor is found with c) areas of wavy texture, which have a lineated appearance. d) large scallops and total mantle cover; this mantle unit is thicker than in a) and the substrate is not visible; mantled areas poleward of this morphology are typically not dissected

fall within this category exhibit both knobby and wavy textures. The wavy texture can appear quite dune-like, but can be distinguished from dunes by its occurrence on steep slopes (with "waves" oriented perpendicular to slope direction), gradation into areas of smooth mantle (not superposed on the mantle), and gradation into areas of knobby texture. This morphology, specifically the knobby texture, is often found on the surface of lobate debris aprons and thicker mantle deposits on pole-facing crater walls. The knobby and wavy texture is most commonly found between ±30-55°, with a peak occurrence at ~ ±45° (Fig. 3b).

Scalloped Terrain The third and final erosional from of the DMT that we have observed is characterized by removal or depressions of large sections of mantle, giving the surface a "scalloped" appearance (Fig. 1d). This morphology is not as spatially extensive as the previous two, but is quite common in several localities (such as northern Utopia). Typically found at latitudes greater than ±40°, with a peak occurrence at ~ ±55° (Fig. 3c), this style of erosion transitions from small "scallops" at lower latitudes to large "scallops" (Fig. 3d) at higher latitudes. The wavy texture described above commonly grades into the small scallop texture, with no well-defined boundary. The mantle associated with this morphology is typically thicker than the mantle found at lower latitudes, lacks craters, and is commonly associated with polygons and cracks, which may be related to periglacial processes [15]. The depth of the scallops varies from several meters to several tens of meters, but the substrate is typically not exposed. This

also suggests that the mantle is much thicker at higher latitudes than at latitudes where the localized complete removal and knobby and wavy textures are observed. The scalloped terrain and the surrounding intact mantle often have a bumpy, stippled texture that is characteristic of the undissected, mantled regions at high latitudes [10].

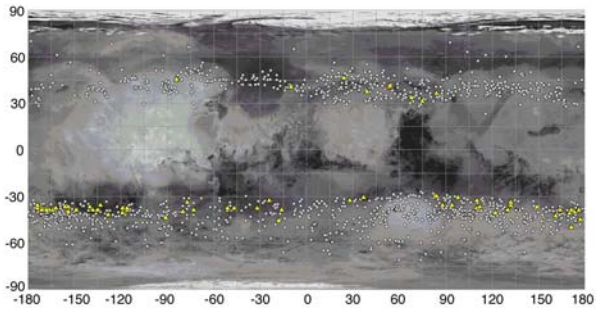

Figure 2. Distribution of examined MOC images with DMT (white) and images with multiple layers of mantle (yellow). This type of layered mantle is primarily found between ±30-40°.

Total Mantle Cover MOC images that are completely mantled with the deposits discussed above, with no exposed substrate, are classified as regions of "total mantle cover". As previously mentioned, areas where large "scallops" are found often fall into this category, where regions of small "scallops" (lower latitudes) do not. This is visible in Fig. 3c, which shows that the latitude range of total mantle cover encompasses part of the scalloped terrain distribution. It should also be noted that most areas of total mantle cover lie outside of the DMT latitude bands and, as expected, lie within the mantled latitude bands. This category of total mantle cover is not part of the DMT subset of MOC images, but rather a separate category. This category was not part of our initial classification and thus represents an incomplete subset of the 13,000 MOC images examined. This is evident by the spatial heterogeneity of this category (Fig. 4), which we believe is solely due to a smaller sample size relative to the other categories. Latitudes greater than ~ ±60° are believed to be completely mantled at all longitudes, which is supported by the Mars Odyssey neutron spectrometer and GRS data [12, 13, 14].

Discussion: The latitude distributions and frequency of occurrence of these different morphologies (Figs. 3, 4) suggests that sublimation, erosion, and removal of the latitude dependent mantles is gradational. The lowest latitudes that contain the DMT are dominated by localized complete removal of a smooth, layered mantle. The occurrence of this morphology decreases with increasing latitude and grades into a knobby and/or wavy texture. This style of incomplete dissection represents the transitional zone between localized complete removal and total mantle cover. This can be seen by the Gaussian-like shape of the knobby and wavy histogram (Fig. 3b), which has an upturn as localized complete removal decreases and a downturn as total mantle cover increases. The DMT latitude bands are regions of transient stability of near-surface ground ice, which is controlled by obliquity, precession, and eccentricity [16]. Stable in these latitudes during previous periods of high obliquity, near-surface ice-rich deposits are currently unstable and would experience sublimation and erosion, consistent with the presence of the DMT [5]. The different erosional styles of the mantle in these regions may be a result of the slow poleward progression of the maximum zone of erosion due to ice-instability. As obliquity decreases, the equatorial latitudes would be affected first, the mid-latitudes second, and the high-latitude regions last.

The observation that the maximum removal (localized complete removal) of the DMT occurs at the lowest latitudes where the mantle is observed is in agreement with this. Furthermore, incomplete removal (knobby and wavy morphology) of the DMT may represent thicker mantle units at slightly higher latitudes that are still experiencing erosion today (though any ice currently present would probably reside below a meters-thick desiccated layer). These mid-latitude regions would be the previous maximum zone of erosion due to ice-instability, in which most or all of the ice has been removed and the lag deposits of loosely cemented dust are now being removed by strong winds. The highest latitudes, which are eroded the least (total mantle cover), may represent even thicker mantle deposits that are experiencing minimal sublimation and erosion today. In this scenario, the regions of large "scallops" (centered at ~ ±55°) would be the current maximum zone of erosion due to ice-instability and poleward limit of dissection due to near-surface ice instability. As obliquity increases (decreases), new ice-dust layers would be deposited (removed) at lower latitudes, with the equatorward extent determined by the amount and rate of water vapor transport and the maximum (minimum) obliquity. The mantles are smooth, locally homogeneous layers that cover the surface uniformly, independent of local geology, topography and elevation. This morphology is most consistent with an orbitally-driven airfall deposit [5, 8, 9]. Moderate-to-high obliquity periods of minimal or non-deposition, coupled with moderate-to-low obliquity periods of extensive removal would cause "unconformities" in this layered sequence. The mantle observed in the transitory mid-latitude bands may have been deposited in this manner, which could account for the differences in degradation and crater frequencies between superposed layers.

Conclusions: Latitude-dependent layers, interpreted to be atmospherically derived ice-dust deposits, exhibit a variety of textures, morphologies, and characteristics. The mid-latitude bands, which host

the DMT, viscous flow features, lobate debris aprons, and terrain softening, have been regions of ephemeral ice-stability over the past few million years. The textures and degradation states of the mantle observed in these latitudes today suggest sublimation, erosion, and removal have been the dominant processes since their emplacement. The smooth, thicker, intact mantles observed at higher latitudes, regions of temporally longer ice-stability, suggest that these same processes have not been dominant at these latitudes in recent history. Accumulation of ice-rich mantle layers at high latitudes and removal of ice-rich mantle layers at lower latitudes accounts for the variations in thickness, texture, degradation state, and may be linked to differences in past or present composition (i.e. ice content) of the mantles. Examining the morphologies and characteristics of these terrains gives insight into where ice-rich deposits exist on or below the surface today that could be accessed by future robotic missions.

References: [1] Soderblom et al., *JGR, 78*, 4117-4122, 1973; [2] Squyres, S. W., *Icarus, 34*, 600-613, 1978; [3] Squyres, S. W. and M. H. Carr, *Science, 231*, 249-252, 1986; [4] Squyres et al. in *Mars*, Univ. Arizona Press, 1992; [5] Mustard et al., *Nature, 412*, 411-414, 2001; [6] Malin, M. C. and K. S. Edgett, *JGR, 106*, 23429-23,570, 2001; [7] Carr, M. H., *JGR, 106*, 23,571-23,593, 2001; [8] Milliken et al., *JGR, in press*, 2003; [9] Kreslavsky, M. A. and J. W. Head, *JGR, 105*, 26695-26711, 2000; [10] Kreslavsky, M. A. and J. W. Head, *GRL, 29,* 2002; [11] Mustard et al., *LPSC 34*, 2003; [12] Feldman et al., *Science, 297*, 75-78, 2002; [13] Boynton et al., *Science, 297*, 81-85, 2002; [14] Mitrofanov et al., *Science, 297, 78-81*, 2002; [15] Mangold et al., *LPSC 33*,2002;[16] Mellon, M. T. and B. M. Jakosky, JGR, 100, 11781-11799, 1995.

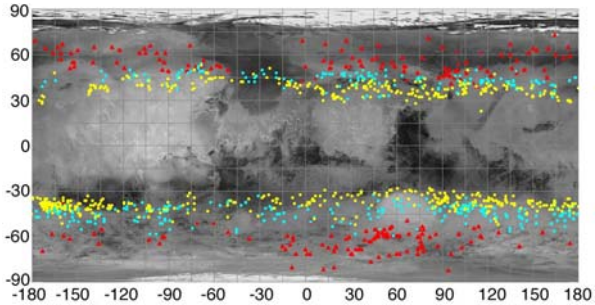

Figure 4. Distribution MOC images with localized complete removal (yellow), knobby and wavy (blue), and scalloped and total mantle (red) morphologies. These three categories show a remarkable latitude dependence. Degree of erosion and removal decreases with increasing latitude in each hemisphere.

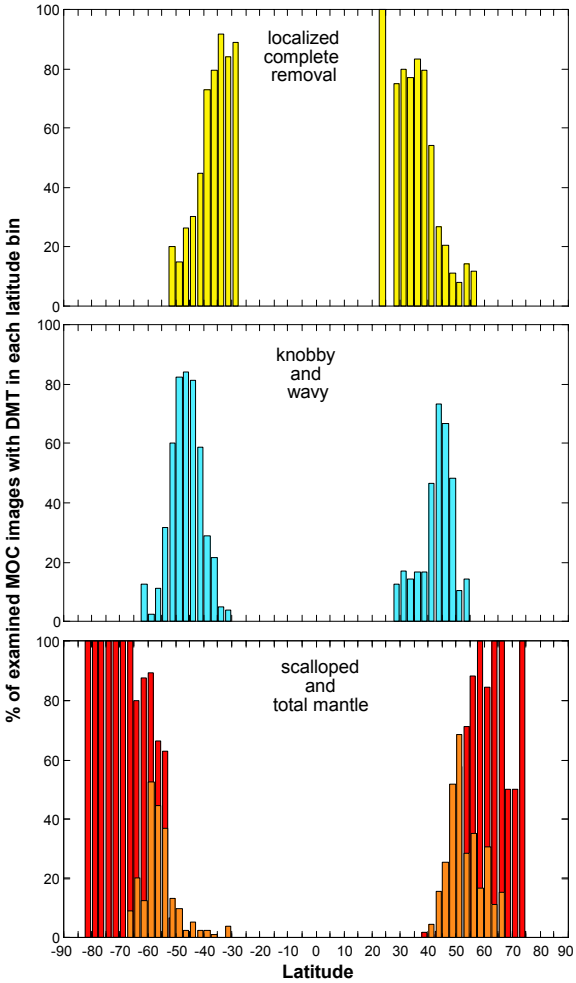

Figure 3. Histograms of the major morphologies of the mantle terrain. Data is in 2.5° latitude bins. a) localized complete removal. b) knobby and wavy dissection. c) scalloped (orange) and total mantle cover (red).