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A recent ice age on Mars: Evidence for climate oscillations from regional layering in mid-latitude mantling deposits

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[1] Two end-member hypotheses have been proposed to account for the emplacement and distribution of ice in the near-subsurface of Mars at mid to high latitudes during recent spin-axis/orbital variation-induced climate change. In the first, diffusion of atmospheric water vapor into and out of a porous regolith forms ice-cemented soils whose latitudinal stability migrates as a function of orbitally controlled climatic conditions. In the alternative hypothesis, atmospheric deposition of ice, snow, and dust produces dusty ice-rich layers during periods of higher obliquity. New image data reveal meters-thick layered deposits exposed on mid-latitude pole-facing slopes supporting the latter hypothesis. These observations suggest that the near surface ice detected by the GRS instrument suite and the Phoenix lander at high latitudes is linked to thick, buried ice that was atmospherically deposited during recent ice ages and that significant amounts of subsurface ice may remain today in the 30–50° mid-latitude regions where fresh craters, imaged by HiRISE, expose abundant ice.

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1. Introduction

[2] *Mellon and Jakosky* [1995] assessed theoretically the distribution and behavior of Martian ground ice during current and past climate epochs and showed that such ice would be stable at lower latitudes during recent periods of high obliquity. In their models, water ice could build up in regolith pore space by the process of vapor diffusion. However, geological observations suggest a different scenario. Using Mars Orbiter Camera (MOC) images, *Mustard et al.* [2001], *Milliken and Mustard* [2003], and *Kostama et al.* [2006] presented morphological observations of latitude-dependent surface textures ranging from smooth and continuous to highly degraded, which they interpreted as evidence for recent deposition of an ice-rich dust deposit currently undergoing desiccation at mid-latitudes. *Kreslavsky and Head* [2002] and *Head et al.* [2003] suggested that latitudinal variations in MOLA-derived surface roughness are the result of these ice-rich sedimentary mantling deposits emplaced during recent obliquity-induced “ice ages.”

[3] Gamma-Ray Spectrometer (GRS) data of hydrogen abundance [*Boynton et al.*, 2002] are consistent with the *Mellon and Jakosky* [1995] predictions for the current latitude-dependent stability of near-surface ground ice, yet the emplacement mechanism of such ice remains debated. Two end-member hypotheses have thus emerged to explain the distribution of ice during recent periods of spin-axis/orbital parameter-driven climate change: 1) atmospheric water vapor is mobilized from high latitudes during periods of climate change and diffuses into and out of the regolith as a function of latitude, thus creating pore ice and perhaps secondary ice lenses [e.g., *Mellon and Jakosky*, 1995; *Mellon et al.*, 2004, 2008], and 2) atmospheric water vapor is mobilized from high latitudes during periods of higher obliquity and atmospheric dust acts as nucleation sites for ice, which then precipitates as a surface layer of dusty snow; during lower obliquity conditions, loss of ice to the atmosphere causes buildup of a dust-rich sublimation lag, inhibiting further sublimation and enhancing preservation of the ice-rich dust layers below to create meters-thick layers representing successive climatic excursions [e.g., *Head et al.*, 2003, and references therein].

[4] In order to assess the viability of these two hypotheses, we analyzed mid-latitude regions where pitting and dissection have exposed the three-dimensional structure of near-surface material. The vapor diffusion end-member hypothesis predicts episodic ice accumulation in regolith pore spaces and subsequent diffusion back to the atmosphere; secondary ice lenses may be present and variations in ice content should be controlled in part by local variations in bedrock/regolith, topography, and pre-existing stratigraphy. The deposition model, conversely, predicts the presence of layers that should be independent of local geology and whose number and continuity should be linked to atmospheric deposition during periods of climate change.

2. Observations

[5] High-resolution ($\sim$25 cm/pixel) data from the High Resolution Imaging Science Experiment (HiRISE) provide the opportunity to examine details of the three-dimensional structure of the subsurface exposed in the partly dissected mid-latitude mantle terrain. We built on the database of Mars Orbiter Camera (MOC) observations compiled by *Milliken et al.* [2003] and *Milliken and Mustard* [2003] and analyzed data in the southern hemisphere (25–50°S) (Figure 1a) from the first two HiRISE releases to the Planetary Data System (PDS). A total of 782 images were analyzed and the major geomorphic characteristics as well as their geological settings were cataloged.

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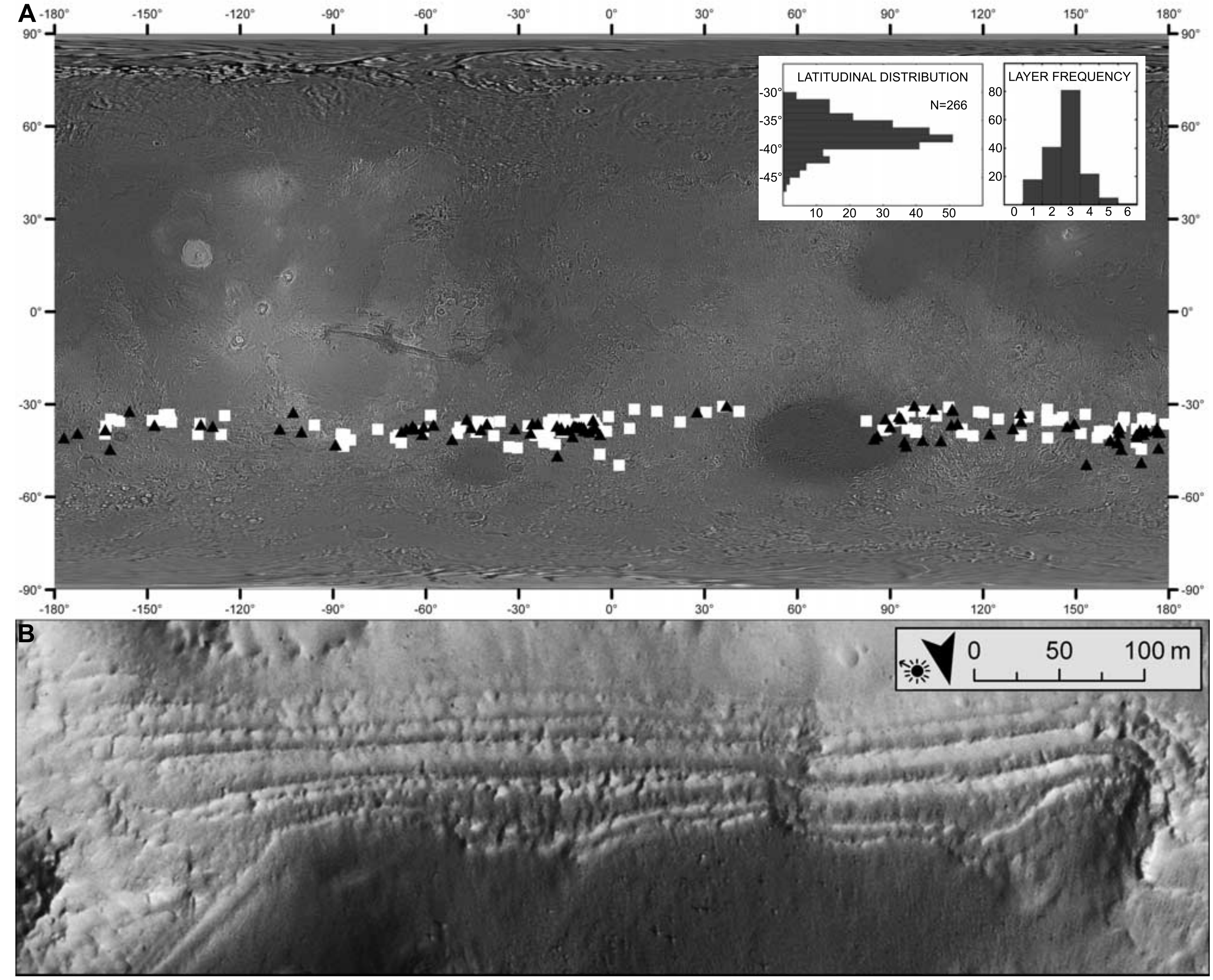

Figure 1. (a) Distribution of MOC (triangles) and HiRISE (squares) images that contain exposures of layering within the upper regolith in association with sublimation pitting. These layers form a mantling unit that drapes pre-existing topography. Insets: left, latitude distribution of layering observations. Right, frequency distribution of the number of layers observed at each exposure in HiRISE observations. (b) Layering within the latitude-dependent mantling unit. This typical exposure shows that stratigraphic layers are a uniform depositional feature of the latitude-dependent mantling deposit and not the result of localized ice lensing. Multiple uniform layers drape large blocks along the southern margin of a 37 km-diameter crater. Layers have been exposed by sublimation pitting on a poleward-facing slope. The stratigraphically lowest portion of the mantle section is at the bottom of this scene; six distinct layers are observed (39.6°S, 343.8°E; HiRISE: PSP_001507_1400).

[6] Our results confirm earlier observations of latitude-dependent morphologies expressed as surface textures. These range from continuous (polygonally fractured to smooth) at higher latitudes, to highly degraded and discontinuous at transitional latitudes, to absent at lower latitudes. Features observed in the transitional regime include sublimation pits, gullies, and lobate flow features [e.g., *Milliken et al.*, 2003]. The normally continuous surface unit has been partially removed in these environments, revealing its three-dimensional structure. Cross-sectional exposures of the surface unit are abundant in this transitional region (Figure 1b) and we examined these in detail to assess the internal structure of the uppermost portions of the surface deposits (auxiliary material).[1]

[7] Un-degraded surface textures in the 20–50°S latitude range appear to drape pre-existing topography, even on steep slopes, as evidenced by muted crater walls and rims. The smooth un-degraded surface is not fractured and occurs preferentially on equator-facing slopes. Small depressions, interpreted to be incipient sublimation pits, are located within some smooth-textured regions (Figure S1), notably in association with the transition to highly degraded textures at lower latitudes. These meters-scale pits are morphologically distinct from very small impact craters in that they are non-circular, do not have raised rims, and exhibit smooth interiors at HiRISE-resolution. A uniform hummocky texture is found when sublimation pits coalesce and no areas of un-degraded surface remain in a region. This hummocky texture is observed predominantly on pole-facing slopes and

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL038554.

is more deeply dissected at lower mid-latitudes. Many mid-latitude (~30–50°) scenes contain areas of both un-degraded and degraded surfaces, with the distribution of the textures controlled by orientation and local slope (Figure S1).

[8] Our analysis shows that orientation and local slope are important controls on the observed texture in the transitional regime between smooth and degraded surfaces. The broad trend is that specific textures are a function of latitude, confirming the results of *Milliken and Mustard* [2003], but local orientation and slope also impart a control: poleward facing slopes exhibit preferential pitting, whereas equator-facing slopes preserve smooth texture (Figure S1). We interpret these relationships to mean that degradation occurs via sublimation, a process well known on Earth [e.g., *Law and Van Dijk*, 1994, and references therein] and long-recognized on Mars [e.g., *Farmer et al.*, 1976]. Sublimation pits develop and expand due to the sublimation of ice, a process that is controlled by insolation, and continues until ice has been completely removed or a sufficiently thick desiccated cover has developed to insulate deeper ice-rich material.

[9] Exposures of internal structure and stratigraphy are observed in a variety of geologic settings between approximately 32°S and 46°S (Figure 1a and inset). The internal structure of the mantle deposit is commonly exposed in cross-section in the transition zone (Figure 1b). These exposures are most often observed in association with gently poleward-sloping regions where a smooth mantle-like surface on flat terrain transitions to a degraded texture on a slope (Figures S2 and S4–S6). We observed 168 exposures of distinctive layering in the mid-latitude mantle in our HiRISE survey. Three layers are most frequently observed, but more layers (up to six) are observed at some localities (Figure 1a inset). We compared the number of layers observed at each locality with latitude and longitude (Figure 1a) but found no compelling spatial relationships.

[10] The most striking aspect of the internal structure of the surface unit is its pervasive layering and the distinctive regularity and lateral continuity of the individual layers (Figures 1a and 1b). Layer thicknesses are estimated to be a few meters and have remarkable lateral consistency; layers can sometimes be traced for several kilometers (e.g., Figures S4–S6). Thickness does not appear to vary substantially between successive layers in a given sequence. We observed no cases in which layers were truncated or pinched out laterally, and no evidence was found for possible lenses within or between layers. In scenes where multiple three-dimensional exposures were observed in adjacent outcrops, the number and character of layers appear to be correlative between the exposures (e.g., Figure S6e), additional evidence that the layers are areally extensive over many hundreds of meters.

[11] Layers are commonly exposed in a step-like manner. In Figure 1b, for example, the lowest layer drapes underlying rough, blocky material, generally smoothing out irregularities. Each successive layer is exposed as a scarp and terrace pair, each pair with very similar characteristics. The scarps are relatively bright, are straight to curvilinear at the hundreds of meters scale, and often have a jagged or serrated form at the meters scale. The terraces appear relatively darker than the scarps, are often irregular in surface topography, and the exposed terrace surfaces are commonly a few meters to several tens of meters wide (Figure 1b). The horizontal resolution of MOLA altimetry is insufficient to determine local layer thicknesses, but regional slopes and outcrop patterns suggest that individual layer thicknesses are on the several meters scale.

[12] In summary, cross-sectional exposures of the surface mantle deposit in the mid-latitudes reveal that its internal structure is characterized by multiple, meters-thick layers that are laterally continuous over many hundreds of meters. The pitting process that produces cross-sectional exposures appears to be controlled by: 1) latitude (ground ice stability), 2) underlying topography (local slope and orientation), and 3) local insolation conditions (pole-facing slopes). These observations and relationships implicate climatic variations in the emplacement of layers, initiation of sublimation pitting, and desiccation of the deposit.

3. Analysis and Interpretation

[13] These observations now permit us to assess the two end-member models of ice emplacement (e.g., vapor diffusion and atmospheric deposition) and their relation to the latitude-dependent, near surface layered structure of the mantle deposit.

[14] Diffusion of atmospheric water vapor into and out of a porous pre-existing regolith predicts equatorward migration of pore ice and secondary ice deposits in the regolith during excursions to higher obliquity [e.g., *Mellon and Jakosky*, 1995]. To a first order, this limits ice abundance to available pore space. If vapor diffusion into and out of the regolith is the dominant process of ice emplacement (and formation of latitude-dependent geomorphic features), then a uniformly stratified, multi-layered deposit that is traceable over long distances would not be expected to form under these conditions. Any layering observed in such deposits would be controlled in part by local topography, local geology, and the nature and distribution of pre-existing regolith. The mantle deposit, on the other hand, tends to drape the surface uniformly and exhibits a distribution that is largely independent of local topography and geology, characteristics more consistent with deposition via airfall. In some cases, ice emplaced in pore spaces by vapor diffusion can serve as nuclei for additional secondary ice, and lenses may develop by internal ice accretion. On Earth such lenses are anisotropic and lack lateral continuity [*MacKay and Black*, 1973, and references therein]. Although extreme cases of ice lensing have been proposed on theoretical grounds [e.g., *Fisher*, 2005], no known examples of this type have been reported on Earth, and the formation of regularly bedded sequences by a secondary ice mechanism is unlikely.

[15] In contrast, equatorward deposition of atmospheric ice, snow, and dust during periods of higher obliquity [*Head et al.*, 2003] is predicted to produce stratified ice-rich mantling deposits. Global climate models predict that at higher obliquities (>30°) the region of surface ice stability expands equatorward and ice is redistributed to the mid-latitudes [*Mischna et al.*, 2003; *Levrard et al.*, 2004, 2007; *Forget et al.*, 2006]. An enhanced atmospheric dust regime, associated with higher obliquity, provides condensation nuclei that promote atmospheric deposition [*Richardson and Wilson*, 2002; *Haberle et al.*, 2003]. During a high-

obliquity peak, a mixture of ice and dust is deposited down to middle latitudes to form a generally continuous meters-thick layer, in contrast to more localized ice accumulations proposed by *Searls et al.* [2008]. During the next period of lower obliquity, near-surface ice becomes unstable at lower latitudes and sublimates, thus concentrating the dust fraction to produce a protective sublimation lag on the surface. Repetition of this obliquity cycle during an "ice age" is predicted to produce multiple layers of interbedded ice and sediment-rich sublimation lags.

[16] Our observations of the spatial distribution and orientation of laterally continuous uniform layers within the upper portions of the mantle terrain are most consistent with an airfall deposition mechanism for these deposits. As discussed above, vapor diffusion processes alone are insufficient to account for the morphologic features of these deposits. Furthermore, gamma-ray and neutron spectroscopy data [*Boynton et al.*, 2002; *Prettyman et al.*, 2004] show high latitude near-surface ice contents significantly above reasonable pore space estimates, which is more consistent with atmospheric deposition of massive ice than simple vapor diffusion [see also *Mellon et al.*, 2008]. The coarse spatial resolution of the GRS data (~600 km/pixel) limits assessment of potential correlations between existing ground ice and discontinuous un-degraded mantle at mid-latitudes. However, latitudinal trends of mantle texture mapped by *Kostama et al.* [2006] and thermal contraction crack polygon terrain documented by *Levy et al.* [2009] support the hypothesis that ice-rich deposits formed at lower latitudes during periods of higher obliquity and that patchy ice may remain in these bands today below a protective sublimation lag.

[17] Pole-facing slopes, though colder on average than other slope orientations, achieve higher peak surface temperatures compared to equator-facing slopes, as described by *Kreslavsky et al.* [2008]. This suggests that peak insolation, rather than average conditions, is controlling modification of the mantle surface texture. Gullies exhibit a similar insolation-controlled orientation preference in this latitude regime [*Milliken et al.*, 2003]. Modest induration of a surface lag or the early development of an insulating desiccated surface layer on the equator-facing slopes aids mantle preservation on these slopes under present insolation conditions. Regions of smooth un-degraded mantling in the mid-latitudes may still harbor near-surface ice below a sublimation lag. These discontinuous regions are well below the detection level achieved by the GRS footprint; however, fresh impact craters observed by HiRISE expose abundant ice [*Dundas et al.*, 2009]. Layered exposures, which are visible because they are currently undergoing erosion, represent the remnants of multiple sublimation lags and are likely desiccated under current conditions.

4. A Refined Model of Mantle Deposition and Modification

[18] The depositional layering observed within the latitude-dependent mantling unit suggests a climatic control mediated by variations in spin-axis/orbital parameters. While precession and eccentricity exert an influence on Martian climate, significant variation in obliquity is the dominant orbital factor [*Laskar et al.*, 2004]. Crater retention ages of *Kostama et al.* [2006] indicate that the emplacement age of the mantling unit surface has a latitudinal trend and ranges from ~0.1 Ma poleward to older equatorward – consistent with recent obliquity history. The obliquity record of Mars over the last ten million years is well constrained [*Laskar et al.*, 2004]. Mars transitioned from a period of high mean obliquity (~35° ± 10°), to the current period of lower mean obliquity (~25° ± 10°), at approximately 5 Ma. However, shorter-duration obliquity excursions exceeding 30° have occurred 15 times in the last 2.5 Myr with an ~120,000-year periodicity [*Laskar et al.*, 2004]. At higher obliquities (>30°), surface ice stability expands equatorward, ice is redistributed to the mid-latitudes [*Mischna et al.*, 2003; *Levrard et al.*, 2004, 2007; *Forget et al.*, 2006], and an associated enhanced atmospheric dust regime provides condensation nuclei that promote atmospheric deposition [*Richardson and Wilson*, 2002; *Haberle et al.*, 2003].

[19] We thus interpret the observed stratigraphy to be the result of obliquity-controlled atmospheric deposition of ice and dust rich layers. During excursions to higher obliquity water is mobilized from polar ice reservoirs, nucleates on dust in the atmosphere, and is deposited in the mid-latitudes forming an ice-rich mantling unit. The end of a high obliquity excursion (the return to lower obliquity) is marked by a decrease in mid-latitude ice deposition, poleward retreat of the ice stability line, sublimation of ice, and development of a protective dusty sublimation lag. In this manner, depositional layers of the mantling deposit are interpreted to be coincident with obliquity periodicity. These layers are modified by sublimation and vapor diffusion during lower obliquity conditions when ice in the deposits is not in equilibrium with the atmosphere. This modification of the mantling units by sublimation may range from complete destruction at the lower-most latitudes, to pitting, partial removal, or enhancement of lags in other regions depending upon insolation conditions.

[20] *Head et al.* [2003] proposed a recent ice age (0.4 to 2.1 Ma) controlled by obliquity amplitude and characterized by accumulation and modification of ice-rich deposits based upon a suite of young, latitude-dependent ice-related landforms. In this paradigm, the current 'interglacial' and the previous 'interglacial' (2.1–2.75 Ma) are periods of low obliquity variation characterized by desiccation and degradation of mid-latitude ice-rich deposits. The dynamics of this type of ice age model were investigated quantitatively by *Schorghofer* [2007] who assumed a global ice deposit formed five million years ago (at high obliquity) and then modeled its ice age-like retreat and re-growth in response to changes in orbital parameters, supporting the interpretation of *Head et al.* [2003].

[21] It is unlikely that the layering is remnant and unmodified from >5 Ma based upon the analyses of *Head et al.* [2003] and *Schorghofer* [2007], both of which imply significant erosion, modification, and overprinting of any regional ice deposits >5 Ma; this is consistent with the very young crater retention ages of these surfaces [*Kostama et al.*, 2006]. Our observations show that more layers are exposed or preserved in some localities relative to others. Subtleties of slope and orientation that contribute to local to regional microclimates are suspected to be responsible for these variations in layer exposure and preservation

[*Kreslavsky et al.*, 2008]. Therefore, we interpret the observed layers to represent the youngest episodes of possible mantling deposition coincident with obliquity excursions for the latitudes where they are observed. This is further supported by the modeling of *Schorghofer* [2007] which indicates that five obliquity excursions during the glacial period (0.4–2.1 Ma) proposed by *Head et al.* [2003] would have stabilized surface ice to ~40°S (the latitudinal extent is quite sensitive to atmospheric humidity), but ice would not have been stable equatorward of 30°S where the mantle deposit is not observed.

5. Conclusions

[22] Numerous outcrops of regionally continuous, meters-thick layers are observed in the transitional regime between smooth and degraded surface textures in the southern hemisphere. Observations of a clear stratigraphy within the latitude-dependent surface mantle and the relationship of these layers to local and regional topography and geology strongly indicate that, among the end-member models, atmospheric deposition of ice, snow, and dust related to geologically recent obliquity excursions formed the unit rather than vapor diffusion into limited pore space. These observations confirm theoretical models that predict stability of atmospherically deposited ice-age layers over these time scales and are consistent with climate models for both the initial emplacement and subsequent degradation of mantle deposits. The near surface high ice abundances derived from Mars Odyssey GRS data [e.g., *Boynton et al.*, 2002; *Prettyman et al.*, 2004] and observed at the Phoenix site [*Smith*, 2009] are likely linked to these recent ice age deposits. Our observations and recent ice-rich crater excavations [*Dundas et al.*, 2009; *Byrne et al.*, 2009] imply that significant amounts of water ice remain at 30–50° north and south latitude at scales well below the hundreds of kilometers footprint of the GRS instruments.

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