Layered mantling deposits in northeast Arabia Terra, Mars: Noachian-Hesperian sedimentation, erosion, and terrain inversion

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Received 30 November 2006; revised 21 March 2007; accepted 10 May 2007; published 4 August 2007.

Thick, layered mantling deposits of different ages occur in several nonpolar regions of Mars and are thought to represent volcanic ash and/or climate-related ice-dust deposition. One such deposit is a layered mantling unit that unconformably blanketed highlands terrain in northeast Arabia Terra during the Late Noachian and/or earliest Hesperian. Shortly thereafter, by the mid-Hesperian, this deposit was substantially eroded; on the basis of its superposed crater population, it appears to have subsequently retained its approximate morphology and distribution in the \( \sim 3.5 \) Gyr since. When the erosion occurred, in the Early Hesperian, the mantling unit was more resistant in some areas than its surroundings, resulting in inversion of relief: craters were transformed into highstanding buttes, and valleys were transformed into isolated ridges. On the basis of the scale of the observed inversion of relief, the magnitude of erosion in northeast Arabia Terra was substantial, up to hundreds of meters. We have used newly available data to assess the nature of the mantling material and probable mechanisms for its deposition and removal. We find that (1) the mantle unit is layered at scales of meters to tens of meters; (2) the deposit has a median thickness of \( \sim 60 \) m, and the thickness of the deposit thins toward the south; and (4) characteristics of the mantling unit, such as its induration, as well as observed pits and fractures, suggest that volatiles may have been incorporated into the mantling unit either during or following its emplacement. Taken together, our observations lead us to favor models for the deposition of the mantling unit involving airfall of dust or ash. Either climate-driven dust deposition or plinian volcanic eruptions from the nearby Syrtis Major volcanic province are plausible candidate models for the emplacement of the unit in time and space.


1. Introduction

To understand the resurfacing history of Mars, we need to assess the character and rates of depositional and erosional processes. As has been recognized since the Viking era, the etched or mantled regions of Arabia Terra provide an excellent laboratory for understanding both deposition and erosion, as widespread mantling deposits were emplaced and then substantially eroded [Grant and Schultz, 1990; Moore, 1990]. The goal of this paper is to present new observations of this mantling unit which help us understand its character, and test possible models for the processes of its deposition and erosion. We focus on a study area from 45 to 55°E and from 0° to 35°N and examine new Mars Orbiter Camera (MOC), Thermal Emission Imaging System (THEMIS), Mars Orbiter Laser Altimeter (MOLA), and High Resolution Stereo Camera (HRSC) data.

The primary mapped geomorphological units in northeast Arabia Terra at the 1:15 million scale are the “etched” (Nple) and “dissected” terrains (Npld) [Greeley and Guest, 1987] (Figure 1a). The etched terrain was defined on the basis of its sculpted or etched appearance, the presence of craters and other depressions filled with smooth deposits, and widespread formation of mesas and buttes. It is characterized primarily by the presence of a layered mantling unit, which appears to be a stratigraphically distinct material unit emplaced unconformably on preexisting Noachian terrain. The global mapped extent of the etched material is \( \sim 10^5 \) km², or \( \sim 0.5\% \) of the surface area of Mars [e.g., Tanaka, 2000], though it is not entirely clear that the etched unit is stratigraphically correlated over its entire mapped extent. The dissected terrain is defined by the presence of valley networks, and is primarily found in the southern portion of the study area.

These geomorphological terrains (Nple and Npld) are not primarily differentiated by the geological materials that are present (except to the extent that the etched terrain is...
Figure 1. (a) Geological context and location of study area. The major units are the Noachian etched terrain (Nple) and the Noachian dissected terrain (Npld) [Greeley and Guest, 1987]. (b) MOLA topography of the study area, which is dominated at the regional scale by large, highly degraded impact basins. Elevations range from +2000 m (white) to −1500 m (purple). (c) MOLA roughness map of the study area based on data from Kreslavsky and Head [2000]. The colors represent three scale lengths: red, 600 m; green, 2400 m; and blue, 9200 m, and smoother surfaces are assigned lighter values. (d) Mapped outcrops of the mantling unit. Comparing Figures 1c and 1d illustrates that the mantle deposit is generally smooth, which is also apparent in images (Figure 3) and profiles (Figure 12). (e) Context map/locations for morphological examples in other figures; thin white box is study region. Basemap MOLA 1/128° elevation hillshade.
related to emplacement and then modification of the mantling unit). Instead, we believe this classification primarily reflects differences in both the intensity and type of geological processes that modified the highlands. The dissected terrain was significantly less modified by the deposition and removal of the mantling unit, although small outcrops of mantle unit are observed in some locations in the Npld, primarily on crater floors (Figure 1d). Conversely, a few valley networks are found in etched terrain, and those that are observed appear to have been degraded, or inverted. Our focus is thus on the processes related to the widespread mantling deposit in northeast Arabia Terra, which is a well-defined material unit.

[5] The goal of this study is twofold: (1) to use new observations to place further constraints on the emplacement and subsequent erosion of the mantling unit and (2) to understand the implications of these processes for the geological history of Mars. We first discuss results from previous studies and the constraints that these have suggested for the geological evolution of northeast Arabia Terra. Then, we examine the detailed morphological and geological characteristics of the mantling material, focusing on the nature of its layering, style of erosion, and physical properties (grain size and induration). MOLA profile data are utilized to help constrain local thicknesses and distribution of the mantle unit. Finally, new crater counting helps constrain the time-stratigraphic scenario for its deposition and erosion.

2. Background

[6] It was recognized using Mariner 9 data that the material in the etched terrain appeared to be superposed or draped on earlier cratered terrain [Meyer and Grolier, 1977]. However, it was difficult to formulate detailed hypotheses for its depositional origin due to the low resolution of the data. The Viking images altered this situation considerably, as sizable portions of northeast Arabia were imaged at up to 50 m/pixel. Key observations based on Viking data include the following:

[7] 1. The mantle unit appears to have been emplaced in the Hesperian upon an old, highly degraded highlands material that dates to the earliest history of Mars [Grant and Schultz, 1990].

[8] 2. In certain locations, the mantling material was armored or more resistant than its surroundings, leading to terrain inversion [Wilhelms and Baldwin, 1988; Grant and Schultz, 1990; Moore, 1990].

[9] 3. In general, the mantling material must have been relatively friable to allow its widespread removal [Moore, 1990].

[10] 4. The material that formed the mantling unit, once disaggregated, appears fine-grained [Grant and Schultz, 1990; Moore, 1990].

[11] On the basis of these and other observations, hypotheses for the origin of the mantling material (or etched terrain) include (1) aeolian, dust or loess deposits [Greeley and Guest, 1987; Schultz and Lutz, 1988; Grant and Schultz, 1990; Moore, 1990]; (2) pyroclastic material (airfall or ignimbrites) [Moore, 1990; see also Hynek et al., 2003]; (3) intrusive volcanic material [Wilhelms and Baldwin, 1988]; and (4) oceanic sediments [Edgett and Parker, 1997].

[12] Grant and Schultz [1990] focused on the timing and nature of gradational processes in a region that includes the deposits found in northeast Arabia Terra. They describe extensive evidence for terrain inversion, and using crater statistics, argue that intense gradation occurred (e.g., removing numerous craters of ~15 to ~25 km in diameter). Grant and Schultz [1990] also found that the oldest crustal material in northeast Arabia appears to be very old (Early Noachian), and that the region underwent significant modification throughout the Noachian and Hesperian (during at least two epochs of gradation). They present evidence that the mantling unit formed during a period of dust deposition followed by wholesale deflation, and argue that the widespread evidence of aeolian erosion and paucity of evidence for volcanic features supports these conclusions.

[13] Moore [1990] also examined the geology and morphology of the mantling unit, though his study area overlapped with only the northern portion of the region examined here. A key observation in his study was abundant evidence that the mantling unit was decoupled from the underlying material; in other words, it was overlaid unconformably upon the underlying unit. Moore [1990] also suggested that the low thermal inertia and easily friable nature of the mantling material indicate that it is fine-grained, and thus favored its deposition as either a differentially welded pyroclastic tuff or a differentially compacted, zonally indurated dust deposit.

[14] Wilhelms and Baldwin [1988] invoked intrusive volcanism (sills), perhaps emplaced into a fragmental or ice-rich layer, as a mechanism for forming the etched terrain. Ridge features recognized by Moore [1990] in the study area were interpreted to be exhumed dikes (see discussion in section 3.1). Generally, however, intrusive mechanisms for emplacing the mantling unit have not been favored by subsequent investigators.

[15] Moore [1990] noted that if material with the characteristics of the mantle unit in the etched terrain were found on Earth, a favored hypothesis for its formation would be water-lain sedimentary deposits, but he discounted this possibility because of the lack of evidence for ocean-sized bodies of water that reached into the Martian highlands. A different conclusion was reached by Edgett and Parker [1997], who presented the case that the etched terrain was a result of ocean-deposited sediments, at least with respect to the layered terrains in western Arabia Terra and Sinus Meridiani. They focus on the smoothness of the etched terrain material, its characteristic layering, and the evidence for sand and smaller grain-size of the material. The case for an early Martian ocean large enough to influence this area is controversial; Carr and Head [2003] suggested that if such an ocean did exist, much of the evidence for it has been subsequently degraded or buried.

[16] Recently, Hynek et al. [2003] have examined the origin of “friable layered deposits” (FLDs), which are generally layered units which have been unconformably deposited upon underlying terrain and were subsequently eroded by aeolian action. Many of the FLDs that they map correspond well to the equatorial layered deposits originally described by Schultz and Lutz [1988] as potential paleopolar deposits (see section 4.1). The FLD map produced by Hynek et al. [2003] includes the widespread etched deposits in central Arabia Terra and Terra Meridiani, but does not
include the etched or mantling deposits in northeast Arabia Terra. The friable mantling unit in this study, however, appears to share many of the characteristics of other regional deposits. Hynek et al. [2003] demonstrate that a plausible mechanism for emplacing the observed FLDs is by ash transport and deposition resulting from pyroclastic activity on the Tharsis rise. It remains unclear how well different regional deposits correlate with each other and whether Tharsis activity can explain the current extent of regional friable layered deposits (see section 5).

3. Geological Characteristics of the Mantling Unit

3.1. Observations From Orbital Image Data and MOLA Topography

[17] Data from the MOC [Malin and Edgett, 2001], THEMIS [Christensen et al., 2004], HRSC [Neukum et al., 2004], and MOLA [Smith et al., 1999] instruments have been compiled for the study region shown in Figure 1. These have been geo-referenced and co-registered in the ArcMap GIS environment to allow for morphological analysis of the mantling unit at a variety of scales. Using ArcMap and these data, we have mapped the present locations of the layered mantling unit (Figure 1d).

[18] A first-order observation from this mapping is that the mantling deposit is found over a wide range of elevations (approximately −1500 m to 1500 m; Figure 2). This is consistent with the observation made by Tanaka [2000] that the etched terrain as a whole has a wide range of elevations across Arabia Terra.

[19] This mapping also reveals that the mantling unit is typically found in one of two relationships with its surroundings and substrate: (1) isolated as free-standing mesas or buttes (some up to tens of kilometers in size and hundreds of meters high, e.g., Figures 3a and 4) or (2) draped in low-lying regions surrounded by higher, preexisting topography, such as the floor of old craters (Figures 3b, 5, and 6).

[20] When we discuss the highlands substrate that the mantle was emplaced upon in this study, we do not wish to imply that this is a single geologic unit (massive or otherwise). It is clear that the highlands crust is complex and frequently a layered amalgam of units [Malin and Edgett, 2000, 2001; Edgett, 2005], which may be sedimentary and/or volcanic material. However, Malin and Edgett [2001, p. 23,487] argue that the mantling unit observed here is simply an upper member of these complex sequences of layered highland material. Our data lead us to a different conclusion: since the mantling deposit was unconformably emplaced upon an older substrate (e.g., Figure 3b) and has distinct depositional and erosional characteristics, we emphasize that it appears distinct from the underlying substrate, in agreement with the observations and interpretations of Moore [1990] from Viking data.

[21] When outcrops of the mantling material are found in isolated locales, as buttes, mesas, or knobs, these often appear to have resulted from inversion of relief of preexisting craters, based on their circularity and size distribution. These presently highstanding outcrops exist at a wide range of scales, and as is the case for craters, there are many more small knobby features of hundreds of meters in scale (e.g., Figure 4) than large circular mesas of tens of kilometers in diameter (e.g., Figure 3).

[22] Terrain inversion also occurred in what appear to be former valley networks, changing them into free-standing ridges (Figure 7) [see also Grant and Schultz, 1990, Figure 4; Williams and Edgett, 2005; Williams et al., 2005]. Evidence that these features inherit the former pathways of fluvial valley networks include (1) their meandering nature and (2) geographic association with (and sometimes a direct connection to) uninverted valley systems. Because of the contiguity of the inverted valleys with craters filled with the mantling material (Figure 7), the fill deposited into both valleys and craters appears to have been the same material and it is likely that the processes that led to inversion in both cases were similar.

[23] The surface of the mantling material is smooth in images with resolution greater than 15 m/px (Figure 3) as well as on the scale of MOLA point-to-point data (over scales of hundreds of meters to kilometers) (Figure 1c) [Kreslavsky and Head, 2000]. Surfaces of the mantling unit are also commonly very flat. This is true for both outcrops that form mesas and buttes, as well as in locations where the mantling material remains trapped in topographic lows (e.g., Figure 3b). However, at the scale of MOC narrow-angle images, surfaces appear rougher, with superposed ridges, dunes, and small knobs (Figure 8). This difference in roughness between scales is common for Mars [Malin and Edgett, 2001]. The ancient age of the surface (~3.5 Gyr; see section 3.4) and observations of the mantling unit suggest that this meter-scale roughness is a result of impact gardening, aeolian erosion, and dune migration.

[24] Observations using Viking data revealed massive layering (at the 100 m scale) in the mantled terrain [e.g., Moore, 1990]. MOC data clearly reveal layering at much finer scales on well-exposed steep cliffs, and the observed fine-scale layering is visible on scarps of the mantle separated by up to 10 km (Figure 9). The thickness of this repetitive layering in MOC images is 5–15 m, and it is possible that the outcrop may be layered at even finer
scales. Within the mantling unit, some layers appear more resistant to erosion than others, creating clear textural contrasts on the exposed scarp face, as is common in terrestrial layered sequences. This may help to explain why the uppermost surface of the mantling deposit is typically smooth on scales of tens of meters, as the mantle may be capped by layers that are particularly resistant to removal. The MOC scale layering in this study area is similar to layering observed elsewhere across Arabia Terra [e.g., Basilevsky et al., 2006; Venechuk et al., 2006].

25 The erosional landforms associated with the mantling unit give clues to its composition and physical characteristics. Edges of the mesas are often highly irregular, almost cuspat, and are frequently characterized by marginal aprons of erosional debris 500 m to 2 km wide (Figure 8). On relatively flat surfaces at the margins of the mantling unit, dunes are commonly observed (e.g., Figures 9 and 10b),

Figure 3. (a) Buttes and mesas of the mantling unit that now stand high above the surrounding knobby plains. Circular mesas in this image illustrate locations where deposits in preexisting craters underwent terrain inversion; the mantling material in the crater was more resistant to erosion deposits in its surroundings which underwent removal. Center of image is 50.5°E, 20.5°N. (b) An example of the mantling unit exposed in preexisting lows, apparently draped on the underlying topography. Center of image is 47.4°E, 15.1°N. THEMIS daytime IR mosaic.

Figure 4. In regions where the mantling unit has been mostly removed, the surface texture in the study region is commonly knobby, often due to small uneroded outliers of the mantle itself. (a) THEMIS VIS image V04105003. (b) THEMIS VIS image V04954006.
representing the mobilization of material eroded off the steep scarps. In some locations, the mantle is extensively pitted at the kilometer scale (Figure 5), and/or fractured (Figure 6). Areas between plateaus, mesas and crater fill are characterized by a distinctive knobby terrain (Figures 4 and 10) which consist of interspersed knobs tens of meters to several kilometers in diameter. Buried craters that are being exhumed are also observed on inter-mesa surfaces where the mantling material has been removed (e.g., Figures 4b and 10).

Where the mantling unit has been eroded, there are a few locations (mostly on basin floors) where curvilinear ridges are observed (Figure 11; see also Figure 5). These ridges appear to be in the process of being exhumed, as they commonly remain partially buried by the mantling material and are only exposed where the mantling material is no longer observed (Figure 11). They are commonly ~50 m wide and ~10–20 m high. Ridges branch in complicated patterns, often with large junction angles of ~60–90°. These junction angles differ from ridges elsewhere that...
are more likely to have formed by inversion of fluvial valley systems (Figure 7) [e.g., Malin and Edgett, 2003; Moore et al., 2003], or as eskers [e.g., Kargel and Strom, 1992; Head and Pratt, 2001] which typically have junction angles of $<$45° [see, e.g., Pieri, 1980]. Moreover, unlike typical fluvial systems, the orientation of curvilinear ridges is not controlled by local or regional topography. We interpret these ridges as exposed subsurface dikes, formed by volcanic or impact processes [e.g., Head and Mustard, 2006; Head et al., 2006], and exhumed when the superposed material (the mantling unit) was removed. On the basis of the evidence that these curvilinear ridges are exhumed, exposed only where the mantling material has been removed, and locally remain partially buried, exposure of these ridges required removal of tens to hundreds of meters of overlying mantle material.

3.2. Grain Size

[27] Virtually all of Arabia Terra (from 0 to 60°E longitude), including the study area, has moderate to low thermal inertia (I~70–200 J/(K m$^2$ s$^{0.5}$)) and high albedo at TES resolution [Putzig et al., 2005; Mellon et al., 2000]. This is consistent with widespread dust or lightly indurated fined-grained material at the surface, as well as minimal surface rock abundances in the upper few centimeters of material (to the thermal skin depth) [e.g., Christensen and Moore, 1992]. It is difficult to distinguish whether this thermal inertia measurement is reflective of properties of the underlying mantling unit or simply a veneer of dust that is currently present due to the recent behavior of the global dust cycle [Moore, 1990]. Nonetheless, in combination with the morphological expression of the mantling unit, Moore [1990] argued on the basis of its friable nature, apparent deposition from suspension, and absence of prominent dune forms that it is made of fine particles.

[28] MOC images have revealed dunes or transverse aeolian ridges [Wilson and Zimbelman, 2004] which are derived from erosion of the mantle (e.g., Figures 9 and 10). Most aeolian ridgeforms found on Mars are thought to be built through saltation, which requires grains that are at least fine sand-size or larger [e.g., Sullivan et al., 2005]. The existence of these aeolian features is thus evidence that the mantling unit is locally eroding into particles of at least fine-sand size. Debris aprons observed on the margin of the mantling unit (e.g., Figure 8) also suggest that the grain-size of eroded particles is fine-sand sized or larger, since preservation of these aprons suggests that grains are above the threshold for dust lifting and removal by wind. Neither of these observations requires that the particles making up the mantle were deposited as fine sand, however, since post-deposition cementation or aggregation of finer particulates (e.g., dust) would be consistent with all the observations of this study.

3.3. Thickness of the Mantling Unit

[29] MOLA point profiles were selected for determination of the thickness of the mantling unit at location where it has well-defined margins. Individual MOLA shots (with a footprint of ~100 m) are spaced at ~300 m, and allow for direct determination of the elevation of the Martian surface without interpolation and are thus favored for use over gridded data where possible. The vertical precision of MOLA measurements is better than a meter on smooth terrain [e.g., Smith et al., 1999]. Thicknesses were determined by direct evaluation of the elevation change on the margin of the mantling unit, a measurement aided by the fact that it frequently has a smooth, flat surface, comparatively flat surroundings, and forms steep scarps. Such measurements were made at 340 locations in the study area (Figures 12 and 13). Thickness measurements are based on three assumptions: (1) regional slope has a minimal influence on the derived thicknesses; (2) derived thicknesses at steep scarps where MOLA measurements allow for thickness estimation are representative of locales where MOLA did not measure; and (3) at the base of scarps on the margin of the mantling unit, preexisting substrate is uncovered.

[30] The first of these assumptions is justified because slopes on the margins of the mantling unit are generally quite steep (10–20°) compared to regional slopes (of a few degrees or less); therefore the regional slope is unlikely to cause a significant error in thickness estimation. The profiles in Figure 12 illustrate this well. The sampling of the Martian surface by MOLA point data is nonuniform, but the second assumption is unlikely to have an effect on estimated thicknesses for two reasons: (1) the mantling deposit is usually flat and smooth, so thickness measurements on one part of an exposure are locally representative, and (2) the average sampling of MOLA points is sufficient that a dense sample of the mantling deposit was possible (Figure 13). Since the base of the steep scarps do not always represent a clear contact of the mantling unit with underlying terrain in
images, the last of these three assumptions is the most uncertain. If, in some locations, the mantling unit is still partially buried, the thickness estimate we derive for the deposit in these locations represents a lower limit.

[31] In the study region, there was a range of measurable thicknesses from a few tens of meters to a maximum of ~450 m, with a median estimate (for all measurements) of ~60 m. The broad trend in the mantling unit thickness is that it thins significantly south of 15°N (Figure 13c). This corresponds to where the etched terrain transitions into dissected terrain and where mantling becomes much less prevalent.

[32] Locally, significant variability in derived thicknesses exist despite the broad regional trends. This variation appears to be primarily controlled by preexisting topography when the material was emplaced: for example, locations near the center of large preexisting craters have thicker fill than at their margins.

3.4. Impact Crater Population

[33] The cratering population which accumulates on planetary surface units can reveal information about both the emplacement of units (for populations that are “in production” and have crater populations that are primarily a function of a well-understood impactor flux) and their degradation (where crater populations deviate from production). THEMIS IR data provide an excellent base for crater counting as they have near-complete coverage in the study area; in the few gaps the Viking MDIM2.1 was utilized as a supplement. Using ArcMap, 3286 craters greater than 500 m in diameter were mapped in the region from 5 to 25°N and 45 to 55°E, a subset of the full study area.

[34] Results of counts on these data are shown in Figure 14 and Table 1. The total crater population that is revealed (including craters in all degradation states) implies that the exposed crust (or basement) determined using the largest craters is very old (Early Noachian; or ~4.0 Gyr, using the
Hartmann [2005] system). However, for craters less than \( \sim 32 \) km in diameter, there is a major divergence in the observed crater population from what would be expected for craters in production (using a Hartmann- or Neukum-type production function) [Hartmann, 2005; Neukum and Ivanov, 2001]. Many fewer craters are found at successively smaller sizes than would be expected for production. The observation of “missing” craters in this size range (or its lower slope in power law space on a crater-size frequency diagram) is consistent with counts by Grant and Schultz [1990] in this study area, as well as with observations in central Arabia Terra by McGill [2000]. Indeed, this missing population of craters from 8 to 32 km in diameter is observed in the crater populations on many Mars highland surfaces [e.g., Barlow, 1988, 1990]. There are two usual models to explain the observation of large divergences in the observed crater population from what would be expected for production on old Martian surfaces: (1) a significant amount of erosion and/or burial has occurred in the highland terrains, resulting in removal of numerous craters from the countable population [e.g., Chapman and Jones, 1977], or (2) the impactor population and resulting size-frequency distribution early in the history of Mars differs from that later in its history [e.g., Strohm et al., 1992, 2005; Barlow, 1988, 1990].

In the first view, the deviation from the expected production function shape is a product of degradation processes during the Noachian. Degradational processes that might cause this deviation include erosion (perhaps by fluvial action) or gradation (sedimentation or burial) [Grant and Schultz, 1990]. One gradational episode in this study area was deposition of the widespread mantling unit.

In the second view, this divergence of the observed population from the expected crater-size frequency shape is a result of changes in the production function itself. If this is the case, it does not require a significant loss of craters from the observable record.

Crater statistics alone cannot readily distinguish between these two possibilities. However, geological observations in this study area suggest that intense removal of craters has occurred, decreasing the population of craters to be counted. The evidence for this is (1) numerous craters over a wide range of sizes are observed in a highly degraded state, suggesting a continuous sequence of crater states from fresh to completely obliterated; (2) circular buttes which appear to have formed by terrain inversion of craters (e.g., Figure 3a), illustrating the intensity of processes that affected craters after their formation; and (3) craters are commonly being exhumed from underlying terrain at a range of scales (Figure 10). In summary, because so many members of the observable crater population have been highly modified, it seems unlikely that the original crater production function is well-preserved.

To help establish a limit on the time that widespread crater-modifying processes ceased in northeast Arabia Terra, we subdivided the fresh crater population (at sizes >8 km) from the population as a whole, using stratigraphic relationships and the morphological characteristics of the craters themselves. Fresh craters were defined as having a well-preserved crater rim and a discernable ejecta blanket; craters in this class often also had well-defined central peaks. On the basis of this fresh crater population, the craters in northeast Arabia Terra were “in production” in the Hartmann isochron system at a time near the end of the Noachian period or beginning of the Hesperian (Figure 14a). This suggests that intense degradation capable of removing or degrading 8 km craters had ended (in the first view), or that any potential transition in the impactor population and production function was complete by that time (in the second view).

Determination of the time of emplacement and removal of the mantling unit was a key goal of our crater counting effort (Figure 14b). We thus divided the total crater population into stages.
population into craters superposed on the mantling unit and those superposed on its surroundings. Craters found clearly superposed on the mantle surface have a population nearly in production for sizes greater than \( \frac{C}{24} 4 \) km, with an end-of-Noachian population (again near the Noachian-Hesperian boundary). The best fit age derived for this population using the \( \text{Hartmann} \) [2005] isochron system is \( \frac{C}{24} 3.60 \) Gyr.

[40] An intriguing result is that the population densities (of craters > \( \frac{C}{4} 4 \) km) on the surroundings of the mantled surface are similar to on the mantle itself, as the surrounding terrain also has a population consistent with accumulation of craters since the Noachian-Hesperian boundary. This suggests that when the mantling material was removed, it must have been removed relatively quickly allowing both surfaces to accumulate similar populations over the last 3.5+ Gyr.

[41] At sizes smaller than 4 km, both the mantling unit and its surroundings have crater populations which deviate from production isochrons. This implies that degradation or removal processes have dominated the small crater population. Aeolian processes are most likely to be responsible for this removal, as attested to by the dunes apparent on both the mantle surface and its surroundings. In this out-of-production, degradation-dominated portion of the crater population (at sizes <4 km), the mantling unit has a higher crater density than its surroundings. This is consistent with the mantle fill material being slightly more resistant to destruction of small craters than its surroundings, which we interpret to be due to the induration of the mantling material which increased its strength. This comparative resistance to erosion is also supported by the observed inversion of relief seen throughout the study area.
To summarize, we interpret the mantle unit to have been broadly draped over the terrain of northeast Arabia Terra in the Late Noachian or at the Hesperian-Noachian boundary. This is younger than ages reported for other layered deposits further to the west [Tanaka et al., 2004], and older than similar deposits elsewhere on the planet [Hynek et al., 2003] (see section 5). Removal of portions of the mantling unit and modification to near its present state appears to have occurred in a geologically short period of time (less than a few hundred million years), since the mantling unit and its surroundings have similar crater populations. This erosion was thus largely complete by the Early Hesperian. In the following section, we integrate this and other observations to test models for the origin of the mantling unit and for its removal.

4. Discussion

4.1. Models for Emplacement of the Mantling Unit

[43] As outlined in the background discussion, the hypotheses presented for the origin of the fill material included aeolian deposition (e.g., dust or loess) [Grant and Schultz, 1990; Moore, 1990], pyroclastic emplacement [Moore, 1990; see also Hynek et al., 2003], volcanic intrusion [Wilhelms and Baldwin, 1988] or deep-water sedimentation (such as from lakes or an ocean [e.g., Edgett and Parker,]

Figure 10. As the mantling material is removed, exhumation of underlying craters is commonly observed at a variety of scales. This exhumation process may have some influence on crater statistics (Figure 13), but comparison of the fresh and total crater populations suggests that destruction of craters is more important than exhumation processes. (a) THEMIS VIS image V04105003. (b) MOC image E0200959.

Figure 11. Ridges are observed where mantling material has been removed, both (a) as long linear features and (b) as more complicated networks of ridges. These are interpreted as exhumed dikes (see text). (a) Center of image is 48.9°E, 31.5°N. (b) Center of image is 50°E, 31.5°N. Portions of HRSC nadir image 2963.
The new observations in this study help constrain the processes responsible for the mantling unit’s emplacement. Exposures of the unit are found over a wide range of elevations (>~3000 m), and the highest elevation mantling deposits are at elevations >1500 m above the datum (Figure 2). Many well-preserved valley networks are found at elevations well below the maximum elevation of the mantling unit in the study area (Figure 2), as well as across Mars [Carr, 2002]. If a deep ocean deposited the mantle, submarine valley networks would have to survive largely unmodified. Furthermore, if an ocean covered this region to the 1500 m contour, it would cover 70% of the surface of Mars, equivalent to a ~2.4 km average global layer. The water volume of such an ocean would be comparable to terrestrial surface inventories [Carr and Head, 2003]. Evidence for such a sizable ocean is controversial [Carr and Head, 2003], especially at a time period as late as the Noachian/Hesperian boundary. Finally, within this study area, the thickness variation and elevations range of the mantling deposit are inconsistent with a model of oceanic sedimentation (Figure 13).

An alternative mechanism for depositing the mantling unit in deep water is lacustrine sedimentation, which commonly produces layered deposits in topographic depressions on Earth. However, the detailed relationships of valleys with craters that contain the mantle cast doubt on whether this is a reasonable possibility. The unconformable emplacement of the mantling unit on preexisting terrain, and the lack of valley incision into the unit, suggest that it was emplaced after widespread fluvial processes operated in this region. Most outcrops of the mantling deposit lack direct connection to valley network-incised terrain (e.g., Figure 3a). The volume of the mantling unit is at least \(10^3\) km\(^3\), and if this volume of sediment had a local source, it would require erosion of tens to hundreds of meters from the neighboring highlands at the time of the emplacement of the mantling unit. Finally, craters that are isolated and distant from highlands watersheds have fill deposits as widespread and thick as those in more favorable locations for fluvial sedimentation. Taken together, these arguments suggest that sedimentation from fluvial action in the highlands cannot explain most of the observed characteristics of the mantling deposit.

Explanations that invoke local volcanic processes, either surface flows or exposed intrusions (as proposed by Wilhelms and Baldwin [1988]), are motivated by the strength of the mantling unit and observation of potential dikes which are exhumed in a few locales in the study area (see section 3.1; Figures 5 and 11). However, widespread evidence suggests that the mantling unit was emplaced unconformably on its substrate (e.g., Figure 3b), which is inconsistent with formation of the mantling deposit via exhumation of intrusive structures. Both intrusive and extrusive volcanic flows are equally problematic for explaining the emplacement of the mantling unit, its erosional style, and the evidence that it is composed of indurated fine-grained particles.

**Figure 12.** MOLA profiles across the steep scarps formed by the mantling material. Measurements across these scarps permits the direct estimation of the thickness of the mantle at a given location (see Figure 13), since the change in elevation across these boundaries is typically greater than changes due to regional topography. The profiles also illustrate how smooth the mantle unit typically is at measurement baselines of hundreds of meters to kilometers. For example, the six MOLA returns on the plateau surface shown for orbit 20307 vary by less than 4 m in elevation over a distance of ~1.8 km.
Moore [1990] argued that the mantling unit was deposited from the atmosphere because of its fine-grained nature, horizontal layering, areal extent, and apparent unconformable emplacement upon preexisting topography. A wide range of new evidence in our study supports the atmospheric dust or ash deposition mechanism as originally proposed by Moore [1990], including (1) meter-scale horizontal layering of the mantling unit, apparent in MOC images (Figure 9); (2) a broad trend in the thickness of the deposit as a function of location (Figure 13); and (3) thickening of the deposit in the deepest portion of preexisting lows.

The new observation of meter-scale, horizontal or subhorizontal layering, coupled with the large areal extent of the mantling unit, strongly suggests deposition of material from suspension. Atmospheric transport of dust or ash has the potential for producing thick, regional layered sequences of fine-grained material [e.g., Moore, 1990]. The repetitive layering observed on mantling outcrops suggests that this deposition occurred in a sequence of discrete events. If the mantling material was deposited as dust, this could be due to periodicity driven by climate; alternatively, the fine-scale layering could result from ash transport and deposition from a series of distant eruptive events.

Both the broad trends in the thickness of the mantling deposit and its significant local variability in thickness help constrain its origin. The existence of a broad trend in thickness implies that the deposition of the mantling unit was a regional-scale phenomenon, not dependent on local sources of material for its deposition. The thickening of the deposit in the deepest portions of preexisting topography appears to have resulted from the ability of these areas to act as a trap during sedimentation or as the material was reworked after its deposition. The preservation of the thickest portions of the mantle in craters may have been aided or enhanced by induration in these locations (see below), as well as by the protection from erosion afforded by crater walls.

Given that atmospheric sedimentation from suspension seems the most plausible mechanism for emplacing the mantle deposit, either ash or dust could be the dominant mantling material. Climate modeling suggests that Arabia Terra is a region that experiences minimal dust lifting (weak winds) in a wide range of scenarios, including under different obliquity conditions [Haberle et al., 2003; Newman et al., 2005]. This is consistent with a hypothesis that Arabia Terra can act as a dust sink. Indeed, on the basis of the dustiness of Arabia Terra at thermal skin-depth scales, it...
appears to be a locus of dust deposition today [e.g., Christensen, 1986].

[51] The mantling deposit appears to be at least locally resistant to erosion, and the deposit must be indurated [Moore, 1990] sufficiently to support 100–300 m high scarps (Figures 3a and 12). The inversion of terrain also requires that some of the mantling unit was more resistant than surrounding terrain. What agents could have caused this induration? One plausible mechanism is incorporation or alteration of the mantling unit by a volatile (most likely H₂O). This could have happened in a primary manner, with ice nucleation on dust grains, or as a secondary process, as groundwater passed through the mantling unit. The coupled deposition of volatiles and dust seems especially plausible in light of the following observations:

[52] 1. Deposition of volatile/dust mixtures are known to occur on the Martian surface at the poles [Thomas et al., 1992]; upon sublimation, disaggregation may result.

[53] 2. Cyclic deposition and removal mediated by the climate and atmosphere is consistent with the observed areal extent and layering of the mantling unit.

[54] 3. Recent work has illustrated the importance of volatile deposition at low-latitudes (0–45°) in recent periods of Martian history, both as latitude-dependent mantles [e.g., Mustard et al., 2001; Kreslavsky and Head, 2002] and as thick regional deposits of ice [e.g., Head and Marchant, 2003; Head et al., 2005].

[55] 4. Changes in the spin-axis orbital parameters of Mars (especially obliquity) have been shown to be a viable transport mechanism for bringing ice to low-latitudes: at high obliquities, water ice stability on Mars moves to low-latitude regions of Mars [Jakosky and Carr, 1985; Richardson and Wilson, 2002; Mischna et al., 2003; Forget et al., 2006].

[56] 5. The spin-axis orbital parameters of Mars are known to be highly variable in the recent past, and this variability has been shown to extend into the planet’s earlier geological history as well [Laskar et al., 2004]. Statistical study suggests that the most probable obliquity value over the past 4 Gyr for Mars is 41.8° (much greater than the present value of ~25.2°), and that there is a ~90% chance that obliquities greater than 60° occurred at some point over that last 3 Gyr [Laskar et al., 2004].

[57] An alternative model proposed for past co-deposition of volatiles and dust in modern low-latitude regions is true polar wander [Schultz and Lutz, 1988]. In this model, locales presently in the low latitudes were at a rotational pole at some point in the past; thus these regions were once focal point for deposition of layered material similar to what is found at the modern pole (the polar layered deposits). As polar wander progressed, these regions were left with paleo-polar deposits [Schultz and Lutz, 1988]. However, both geophysical [Grimm and Solomon, 1986] and geological [Tanaka, 2000] analyses cast doubt on whether polar wander on Mars occurred, at least as late as when the mantling unit and other friable layered materials were deposited. Most potential paleo-polar or friable layered deposits on Mars, including the mantling deposit discussed here (see section 3.4), appear to be Late Noachian or younger [Hynek et al., 2003], after Tharsis was mostly in place [Phillips et al., 2001]. Moreover, recent studies imply that transport of water ice to near-equatorial latitudes can occur in the present polar configuration due to obliquity variations alone [e.g., Mischna et al., 2003]; thus characteristics of deposits thought to require polar wander may have a simpler explanation.

[58] Incorporation of water ice during deposition or subsequent infiltration of groundwater can lead to substan-
Fenton and Richardson [2007] have suggested that explosive volcanism is potentially a more important process for all Martian volcanoes (including basaltic shields) than for those on Earth, due to the lower atmospheric pressure and greater eruption speeds on Mars. Deposits from explosive eruptions might be recognized by mantling deposits over tens to hundreds of kilometers of terrain [Wilson and Head, 1994; Hynek et al., 2003]. Moreover, recent work with Mars General Circulation Models (GCMs) suggest that over a wide range of orbital parameters and climate scenarios, east-to-southeast winds from Syrtis Major toward the study area are common, due to the Isidis basin [e.g., Madeleine et al., 2007; see also Fenton and Richardson, 2001]. Wind predominantly from the southeast across Syrtis Major (centered at $67^\circ$E, $9^\circ$N, see Figure 1a) would lead to the observed thickness distribution of the mantling deposit, with the thickest portions near $50^\circ$E, $20^\circ$N and thinning significantly to the south of $15^\circ$N (Figure 13). These factors suggest that Syrtis Major is an excellent potential source for the mantling unit.

Recently, Wilson and Head [2007] have suggested that more water may be exolved during a Martian pyroclastic eruption than is typical on Earth, which would provide a potential source of volatiles that may become incorporated in the ash deposit. In this model, volatiles incorporated into the mantling unit may be related to the volcanic event itself. In the future, we hope to construct a forward model for an eruption on Syrtis Major, utilizing the new parameterization developed by Wilson and Head [2007] for expected particle size distributions and a Mars GCM to directly trace ash transport following an eruption. Further comparison of this sort of modeling with the geological record will help constrain the viability of such a scenario. Distinguishing between dust or ash deposition for the origin of the mantling unit will require both further modeling and new observations; indeed, a combination of factors may be involved.

### 4.2. Models for Erosion and Terrain Inversion

From our observations, the mantling unit appears to have been initially widespread, and subsequently has undergone erosion and inversion of relief. These observations also suggest that the magnitude of removal must have been extensive, since terrain inversion has left isolated mesas, buttes and knobs hundreds of meters high (Figure 3), and the mantling material is deeply fractured and pitted buttes and knobs hundreds of meters high (Figure 3), and the mantling material is deeply fractured and pitted (Figures 5 and 6). Crater counts suggest that this may have occurred in a geologically short period of time, perhaps less than a hundred million years (Figure 14). Combining this magnitude of erosion and time estimate suggests an average erosion rate of $1 \text{ m/Myr}$.

On the basis of analysis of Viking data [e.g., Greeley and Guest, 1987; Moore, 1990], the preferred hypothesis for erosion of the mantling unit in northeast Arabia Terra was aeolian erosion. No evidence exists that the mantling unit was modified by fluvial erosion or transport, and no partial alteration of the material in which it is found. One process important for the evolution of the mantling deposit is cementation of dust or ash grains, which may have indurated the unit and protected it from removal. Cementation resulting from water-sediment interactions are known to have altered sedimentary material at the Meridiani landing site [Squyres et al., 2004], though the indurating or cementing agent and environmental conditions for the northeast Arabia Terra deposit are unknown. Another potentially important process linked to volatiles is direct removal of material from the mantling unit to the atmosphere, which might help explain unusual erosional characteristics of the deposit (see next section).

If the deposit is made of ash rather than dust, a plausible local source of ash exists just east of the study region. Syrtis Major has an Early Hesperian surface age [Hiesinger and Head, 2004] essentially consistent with the mantling unit’s apparent emplacement age. The broad structure of Syrtis is similar to other highland volcanic provinces thought to involve abundant pyroclastic volcanism [Greeley and Crown, 1990; Crown and Greeley, 1993]. Wilson and Head [1994] suggest that explosive volcanism is potentially a more important process for all Martian volcanoes (including basaltic shields) than for those on Earth, due to the lower atmospheric pressure and greater eruption speeds on Mars. Deposits from explosive eruptions might be recognized by mantling deposits over tens to hundreds of kilometers of terrain [Wilson and Head, 1994; Hynek et al., 2003]. Moreover, recent work with Mars General Circulation Models (GCMs) suggest that over a wide range of orbital parameters and climate scenarios, east-to-southeast winds from Syrtis Major toward the study area are common, due to the Isidis basin [e.g., Madeleine et al., 2007; see also Fenton and Richardson, 2001]. Wind predominantly from the southeast across Syrtis Major (centered at $67^\circ$E, $9^\circ$N, see Figure 1a) would lead to the observed thickness distribution of the mantling deposit, with the thickest portions near $50^\circ$E, $20^\circ$N and thinning significantly to the south of $15^\circ$N (Figure 13). These factors suggest that Syrtis Major is an excellent potential source for the mantling unit.

### Table 1. Size-Frequency Distributions for Crater Counting in Northeast Arabia Used for Figure 14

<table>
<thead>
<tr>
<th>Diameter (Bin Center, $\sqrt{2}$-inc), km</th>
<th>N</th>
<th>Frequency, N/km²</th>
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<tr>
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</tr>
<tr>
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<td>1.08E-04</td>
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</tbody>
</table>

⁵Area: 661,810 km².
⁶Area: 661,810 km².
⁷Area: 523,020 km².
⁸Area: 138,790 km².
reasonable pathways of sediment out of the low-lying basins of the study area exist.

[63] A difficulty for the aeolian removal model is that recent GCM analyses predict very low deflation potentials in the study area under present conditions (deflation potential is defined as a depth of dust that can be removed from a surface during a given period of time, and is primarily a function of exposure to winds sufficient for dust-lifting) [Haberle et al., 2003]. Low deflation potential also appear to exist in the study area over a variety of spin-axis scenarios [Haberle et al., 2003]; indeed, in many scenarios, net deposition of dust in Arabia Terra seems likely [Newman et al., 2005]. Thus, along with observations that suggest it is a dust sink today [e.g., Christensen, 1986], this modeling suggests it may also have been a dust sink in the past as well.

[64] One mechanism that may explain the apparent rapid erosion of the mantling deposit is if some of the material lost from the mantle was due to direct loss of a volatile component to the atmosphere via sublimation. Sublimation of surrounding material to the atmosphere has been proposed as a mechanism for forming pedestal craters [e.g., Barlow, 2006], which are perched above their surroundings like the inverted craters seen in this study area (though pedestal craters are less modified than the inverted craters seen here). Sublimation may also help explain the formation of large pits, moats, and fractures in the mantle material (Figures 5 and 6), which are hard to explain by aeolian erosion alone. However, even if direct loss of volatiles to the atmosphere played a role in modifying the mantling deposit, a significant amount of aeolian transport of disaggregated material away from the northeast Arabia deposit must have occurred, eroding not just portions of the mantling unit but also preexisting highlands materials. This may require different climate conditions and deflation potential in the Early Hesperian from what is observed and modeled today. One candidate scenario is a thicker early atmosphere.

[65] The terrain inversion that is observed in northeast Arabia Terra is striking, but inversion of relief of this sort is not unique to this location on Mars. Pain and Ollier [1995] provide type examples of terrestrial environments where inversion of relief is known to have occurred in a variety of circumstances, such as alluvial deposits in Australia where terrain inversion has been driven by duricrust formation. On Mars, terrain inversion has been observed over a variety of scales in other locations on the surface [see, e.g., Malin and Edgett, 2003, footnote 13; Williams and Edgett, 2005; Burr et al., 2006]. This is likely to be due to the confluence of many factors on Mars which create a potential for terrain inversion [Pain and Ollier, 1995], including duricrust formation [e.g., Mutch et al., 1976], surface armoring [e.g., Conca, 1982], and aeolian erosion [Greeley et al., 1992]. Combined with the lengthy exposure of material on the surface due to low rates of surface change [Golombok and Bridges, 2000], these slow processes, acting over time, may have led to much of the inversion of relief observed on Mars.

[66] The sequence of processes that led to the inversion of valleys in northeast Arabia Terra (Figure 4) seem to differ from what caused inversion of the sedimentary deposits in Eberswalde crater, however [Malin and Edgett, 2003; Moore et al., 2003]. In Eberswalde, the inversion of relief is believed to have resulted from preferential preservation of relatively coarse grained channel deposits upon post-depositional aeolian erosion. We interpret the inversion of valleys in northeast Arabia Terra to result from deposition of mantling material that filled in and preserved valleyforms, rather than preferential preservation of fluvial sediments related to the valleys themselves. Thus, when small valleyforms are found exhumed out of the rock record in other environments on Mars [e.g., Williams and Edgett, 2005], it is possible that the materials marking the past presence of valleys are not necessarily fluvially derived sediments themselves. The cause of terrain inversion in a given location needs to be examined on a case-by-case basis.

4.3. Synthesis of the Geological History of Northeast Arabia Terra

[67] A schematic illustration of the geological history of northeast Arabia Terra is shown in Figure 15. The Early Noachian age of the highlands material is revealed by the continued presence of 19 discernable craters larger than 50 km in the count area (5 to 25°N, 45 to 55°E), though these have been highly degraded by subsequent processes. Impact cratering appears likely to have dominated all other processes during the early history of the region. As in other regions of the highlands, valley networks incised the highlands terrain, but these failed to drastically reshape the topography [e.g., Stepiniski and Collier, 2004] and appear to be relatively immature compared to Earth. The primary geomorphic effect of valley networks is interpreted to be local redistribution of sediment.

[68] During the latest Noachian or earliest Hesperian, a mantling deposit was emplaced as airfall in a series of layers. This was unconformably deposited on the valley network-incised terrain in a spatially continuous or near-continuous way, thinning to the south. Material was either deposited or reworked into especially thick deposits (up to ~0.5 km) in preexisting low-lying terrains (impact basins and valleys). Mantling material in these low areas may also have been preferentially indurated, perhaps resulting from an incorporation of volatiles during deposition or infiltration of volatiles after emplacement. Removal of the mantle unit was relatively abrupt, and removal may have been aided by sublimation of volatiles to the atmosphere. The local induration of the mantling material meant that it was stronger than its surroundings in certain locations, leading to inversion of relief. Subsequent to the period when the mantle was being removed, relatively little modification of the remaining etched terrain has occurred; the primary processes that continue to alter the terrain are small impacts and aeolian modification.

5. Implications and Relationships to Other Deposits on Mars

[69] A number of units with characteristics similar to the mantling material in northeast Arabia Terra are found elsewhere [e.g., Tanaka, 2000], especially in regions with “frangible layered deposits” as delineated by Hynek et al. [2003], such as the Medusae Fossae region, Aeolis Mensae, central and western Arabia Terra and Terra Meridiani and on the floor of Valles Marineris. All FLDs appear to consist of
material that is layered and unconformably emplaced on underlying materials. FLDs commonly have erosional characteristics that make them appear “etched.” Differences in the detailed morphology of these units exist, however: for example, yardangs are rare in northeast Arabia Terra, but commonly found on the Medusae Fossae Formation [e.g., Bradley et al., 2002]. This might reflect different erosional regimes after deposition (higher winds at Medusae Fossae) or different strength of the material (perhaps due to differences in grain-size or layer thickness).

[70] Hynek et al. [2003] provide arguments that friable layered deposits on Mars share a common origin via explosive volcanism and ash deposition. They also present the case that the FLDs may have been fed by a common source: the volcanoes on the Tharsis rise. However, as Hynek et al. [2003] note, the evidence for the synchronous formation of various FLDs is tenuous. For the study area we examine, the superposed crater population on the mantling unit makes it unlikely that its deposition occurred after the mid-Hesperian, and it was apparently emplaced by the Early Hesperian (Figure 14). At least some FLDs appear to have experienced deposition since the mid-Hesperian; in particular, the Medusae Fossae Formation appears to at least locally superpose relatively young (Amazonian) volcanic flows [Hynek et al., 2003; see also Malin and Edgett, 2001, Figure 88]. It is possible that this later activity may represent aeolian reworking of the material, but in general there is no particular reason to think that the northeast Arabia Terra deposit is time-synchronous with all other FLDs.

[71] It is also worth considering whether FLDs appear to be derived from a common source region. Recent work by Wilson and Head [2007] suggests that the minimum size for ash particles resulting from an eruption is controlled by the smallest gas bubbles that nucleate in the ascending magma, which they estimate to be at least a few tens of microns. Particles > 50 μm are unlikely to be transported more than a few thousand kilometers from their source, though the specific attainable transport distance depends on particle density, atmospheric conditions, and emplacement location [Hynek et al., 2003; Wilson and Head, 2007]. Given these results, Syrtis Major is a more likely ash source for the observed deposits than volcanoes on Tharsis, which is ~9000 km away. Other FLDs, for example the Medusae Fossae Formation, are closer to Tharsis (especially in its eastern portions) and are more likely to have been derived from a Tharsis source.

[72] Much recent work has emphasized the importance of exhumation as a geological process on Mars [e.g., Malin and Edgett, 2000, 2001; Edgett, 2005]. It is clear that exhumation of at least hundreds of meters has occurred in northeast Arabia Terra, supporting this view. In contrast to some of the examples presented by Malin and Edgett [2001], where exhumation appears to be a recent or ongoing process, the cratering record in this region suggests that most of the removal of the mantling unit occurred prior to the Late Hesperian. Nonetheless, burial and exhumation of the terrain was intense enough to turn craters into knobs, and to apparently remove many craters from the record entirely, especially at small diameters. Thus we concur with Malin and Edgett [2000] that one needs to use extreme caution when attempting to understand crater populations.
on a specific surface, because craters small enough to be removed by subsequent processes will fail to provide true formation ages. This does not decrease the importance of crater counting, however, because where the loss of craters has caused the population to deviate from production, the population then acts as an indicator of the intensity of resurfacing processes [e.g., Hartmann, 2005; Grant and Schultz, 1990], as we have shown here.

6. Conclusions

[71] Observations of the layered mantle unit in northeast Arabia Terra indicate that hundreds of meters of material were deposited on the surface, likely as airfall. Both dust and ash are plausible sources of this material. Removal of the mantling unit appears to have been relatively abrupt, and differential induration of the mantling material caused significant terrain inversion. This differential induration, as well as other characteristics of the mantling unit, suggest that volatiles may have been incorporated into the deposit. The fact that northeast Arabia Terra experienced burial by hundreds of meters of material, followed by rapid, widespread erosion and exhumation of underlying terrain, helps to clarify the complex depositional and erosional history of Mars.

[74] Acknowledgments. We are grateful for detailed reviews by Nadine Barlow and Jeffrey Moore, which helped improve the manuscript significantly. We acknowledge the THEMIS, MOC, and MOLA teams for data used in this study. We also thank the HRSC Experiment Teams at DLR and Freie Universitaet Berlin, as well as the Mars Express Project Teams at ESTEC and ESOC, for their successful planning and acquisition of the HRSC data and for making processed data available to the HRSC team. Jay Dickson, Gil Ghatan, Misha Kreslavsky, and David Shean participated in helpful discussions, and Bill Fripp provided computer support for this research. We gratefully acknowledge support of this research by the NASA Graduate Student Research Program (C.I.F.), the NASA Mars Data Analysis Program (J.W.H.), and the NASA Mars Express HRSC Investigator Program (J.W.H.).

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