Evidence for extensive denudation of the Martian highlands

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ABSTRACT

High-resolution topographic data from the Mars Orbiter laser altimeter reveal evidence for widespread denudation from Margaritifer Sinus to northern Arabia Terra, an area of $\sim$1 $\times$ 10^7 km^2. A major resurfacing event is indicated by: (1) a heavily degraded landscape hosting numerous inliers, (2) truncation or absence of valley networks, and (3) a break in slope at the edge of early to middle Noachian plateau materials. Geomorphic mapping was completed on the type locale of denudation (0°–30°S, 0°–30°W). Superposition relations and crater counts for geomorphic units indicate that large-scale resurfacing took place in the late Noachian, eroding the Martian highlands and resulting in transportation and deposition of $\sim$4.5 $\times$ 10^6 km^3 of sediment in the northern plains. This is equivalent to a 120-m-thick uniform layer of sediment on the surface of Mars north of 30°N. Geomorphic mapping and crater counts limit the timing of denudation to the late Noachian, an interval of 350–500 m.y. Using this limit, we estimate a minimum rate of denudation of 2.0 μm/yr, comparable to denudation of typical slopes in a temperate maritime climate on Earth. The morphology, rate of denudation, and extensive nature of upland degradation suggest that precipitation-fed surface runoff is the most likely geomorphic agent capable of such a process, indicative of a warm, wet Mars during the late Noachian Epoch.

Keywords: Mars, denudation, erosion, landscape evolution, precipitation.

INTRODUCTION

Characteristics of the Martian highlands, including the subdued, infilled, and heavily modified nature of craters, an atypical size-frequency distribution of craters, and degraded valley networks (quasi-dendritic features potentially formed by flowing water; Carr, 1996), have led many workers to conclude that the Martian highlands have undergone extensive resurfacing (summary by Craddock and Maxwell, 1993). Proposed resurfacing processes include eolian or volcanic deposition (e.g., Arvidson et al., 1980), fluvial erosion (Chapman and Jones, 1977), and fluvial erosion coupled with local redeposition (Craddock and Maxwell, 1993). Chapman and Jones (1977) argued that resurfacing abruptly ceased in the Noachian at the end of heavy bombardment [Martian time is divided into three major epochs: Noachian (oldest), Hesperian, and Amazonian (youngest)], whereas Craddock and Maxwell (1993) hypothesized that termination of resurfacing was much more gradual. Each of the scenarios envisaged here indicates a drastically different history with implications for the geologic, geomorphic, and climate histories of Mars.

Using high-resolution topographic data from the Mars Orbiter laser altimeter (MOLA) instrument on the Mars Global Surveyor mission (Smith et al., 1999), we have gathered evidence for a major fluvial resurfacing event in the Martian highlands. We completed detailed geomorphic mapping for the Margaritifer Sinus region (0°–30°S, 0°–30°W), where resurfacing appears most evident. In addition, evidence from adjacent areas suggests that this was not a localized event, but one that affected at least 1 $\times$ 10^7 km^2 (an area equivalent to the European continent) of the cratered uplands. The topographic information allows for the first time a separation of younger, low-standing fluvially reworked terrains from older, high-standing erosional remnants. The newly acquired MOLA data also allow the volume of eroded material to be sensibly determined and minimum erosion rates to be estimated. The erosional episode was limited in time to no more than several hundred million years, and occurred ca. 4 Ga. The scale of the processes involved strongly suggests, but does not demonstrate uniquely, that precipitation must have played a major role in landscape denudation in this region of Mars.

DETAILED GEOMORPHIC MAPPING OF MARGARITIFER SINUS, MARS

In the Margaritifer Sinus region, fine-scale (60 pixels/degree longitude, 30 pixels/degree latitude) MOLA grids, in conjunction with Viking and released Mars Orbiter Camera images, have allowed the distinction of rugged inliers of older, heavily cratered, topographically high material, from younger, relatively sparsely cratered, topographically lower, smooth depositional units (Fig. 1). Margaritifer Sinus is an excellent area to examine the nature and timing of resurfacing in the cratered uplands because of the inliers, which are erosional remnants, and the strong evidence of past surface water (Goldspiel and Squyres, 1991; Grant, 2000). Geomorphic mapping was completed at a 1:3 000 000 scale (Figs. 2 and 3) to elucidate regional geologic, geomorphic, and inferred climate histories and to help define the age of denudation and volumes of material removed. Mapping of lithostratigraphic units is possible in places on Mars based on topographic, spectral, and morphological characteristics (Tanaka et al., 1992). For example, unit HNl described in Figure 2 has a distinct spectral signature, sharp contacts, a uniform crater density, and is superposed on all surrounding materials. Other terrain does not have entirely definitive characteristics and must be mapped on morphology and crater density. Units that have undergone significant modification by surface processes since their formation constitute geomorphic units. Recent acquisition of fine-scale topography, spectral properties, and high-resolution Mars Orbiter Camera images has allowed the subdivision of material that was previously mapped as single-age middle Noachian (Scott and Tanaka, 1986) into several distinct geomorphic and geologic units with varying ages.

Much of the load of the Tharsis igneous complex (Tanaka et al., 1992) was emplaced in Noachian time (Banerdt and Golombek, 2000). Recent modeling indicates that membrane loading of the lithosphere by Tharsis has created both a topographic trough and negative gravity anomaly that rings Tharsis and a structural high and positive gravity anomaly over Arabia Terra (Phillips et al., 2000a). In the study area, a prominent segment of the trough (termed the Tharsis trough) is seen in the western section, as is a part of the structural uplift (termed the Arabia bulge) in the eastern part of the mapped area (Fig. 1).

Our mapping (Figs. 2 and 3), and the relative time sequence of geomorphic units established by superposition and crater counts[1], show the following. Topographically high plateaus, mountains, and large impact basins are the oldest units and are mapped as rough terrain (Nr). Multiple, primarily volcanic, resurfacing events occurred throughout the Noachian (Grant, 2000), serving to modify, embay, and bury some of the ancient surface, forming the ridged (Nri) and subdued cratered (Nsc) materials.

A majority of the valley networks were carved on middle-late Noachian terrain, forming the dissected unit (Nd). The structural uplift

[1]GSA Data Repository item 2001045, Correlation of mapped units and corresponding geologic events, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

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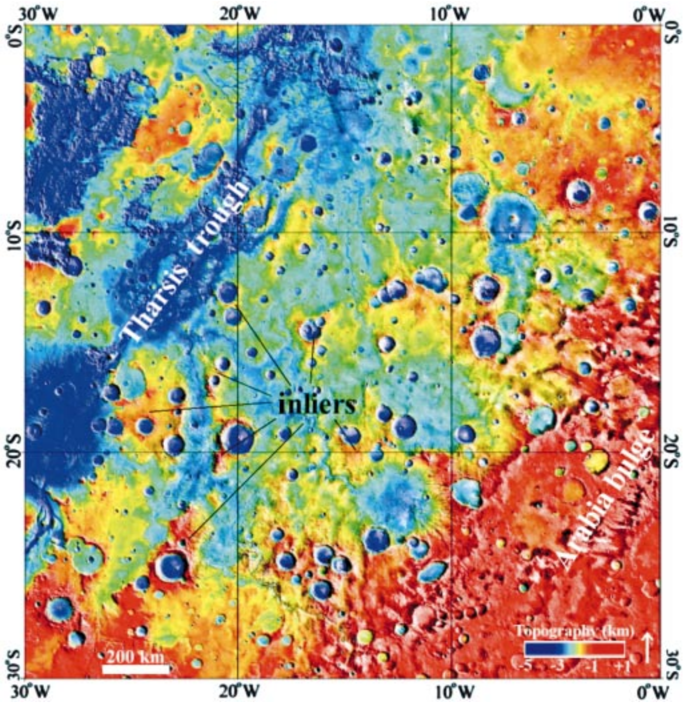

Figure 1. Mars Orbiter laser altimeter digital elevation model of Margaritifer Sinus region, Mars. Tharsis trough is seen trending northeast, containing series of basins and valleys connected apparently to flow from Argyre impact basin (Parker et al., 2000). Extensive fluvial erosion is seen through central part of image, directed toward trough. High-standing, heavily cratered inliers (seen in orange and yellow) are abundant in this area (examples indicated). Ancient Noachian plateau (seen in orange in southeast) is oldest and topographically highest region in image. Pole-to-pole topographic slope has been removed in data (Smith et al., 1999) to emphasize regional variations in elevation.

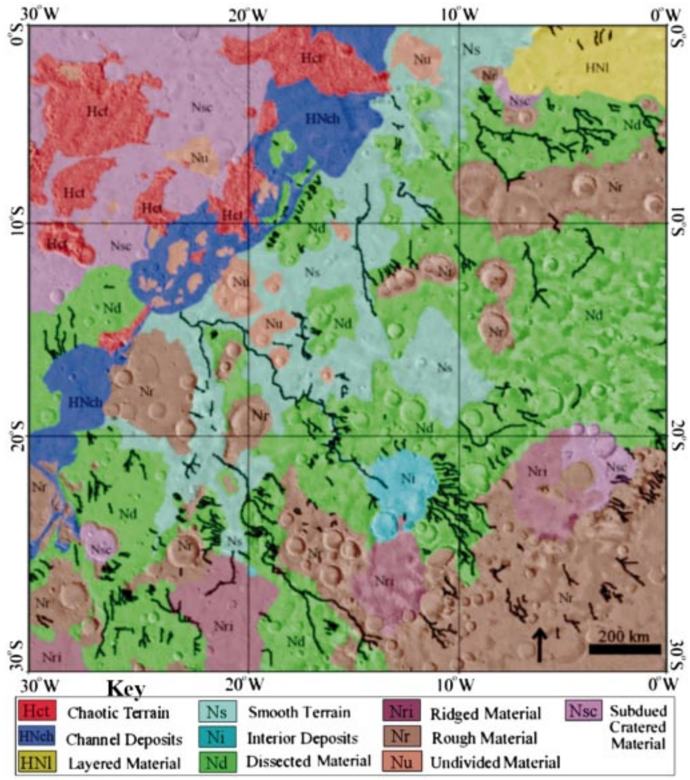

Figure 2. Geomorphic map of Margaritifer Sinus region (mercator projection). Note termination of many valley networks (seen in black) at contact with smooth material (Ns). Mapped craters and structural features are omitted for clarity. Abbreviated description of map units follows. Hct and HNch—Chaotic and flood-plain materials related to emplacement or modification by water, as described by Scott and Tanaka (1986). HNl—Low-relief, hematite-rich, layered, friable plains superposed on surrounding units. Ns—Smooth material exhibiting little relief, occupying low-lying basins, and topographically lower with smaller gradient and fewer valley networks than dissected terrain (Nd). Embays topographically higher inliers. Ni—Hummocky terrain with interspersed smooth material found within Parana basin (lat 22°S, long 12°W), which has breached rim on downslope side and ~800 km sinuous valley emanating from break. Nd—Moderate to rough terrain, intermediate to heavily cratered, with many well-integrated valley systems. Nsc—Smooth, gently undulating plains with high crater density, although many craters are partially buried or ghost craters. Nri—Smooth material found within higher topographic reaches, exhibiting ridges of consistent orientation locally, but not globally. Nr—Heavily cratered rugged terrain, consisting of highly degraded impact basins and knobs, found within highest reaches of mapped region. Nu—Composed of older, topographically high terrain that could not be assigned to specific geomorphic unit.

of the Arabia bulge and the structural depression of the Tharsis trough, along with the pole-to-pole northerly downslope (Smith et al., 1999), likely provided topographic gradients that aided valley network formation and controlled their direction (Phillips et al., 2000b). This may be analogous to the uplift of the Colorado Plateau, with subsequent erosion and transportation of sediment off the flanks.

Formation processes of valley networks are still controversial; the debate is largely focused on the relative roles of surface runoff and groundwater processes. In the mapped region, the morphology of the valleys and associated networks (v-shaped profile, sinuous, high density, and high valley order) and the observation that numerous valleys originate near the tops of crater rims or hilltops (Fig. 3) indicate that precipitation and surface runoff may have played a major role in their formation. Some valleys show morphologies more consistent with a groundwater-sapping origin (u-shaped profile, low density and order, and alcove-like terminations), suggesting that subsurface water was also important. Therefore, both precipitation and groundwater certainly contributed to degradation in the Margaritifer Sinus region, but the relative importance of each erosion mechanism is unclear. These results are consistent with previous work completed on the south-central part of our study area (Grant, 2000).

In the mapped region, incision occurred primarily on high topographic gradient areas, many valley networks terminating at the gently sloping, topographically lower, smooth material (Ns) (Fig. 3). We hypothesize that steeper slopes were preferentially incised and eroded, forming the dissected terrain (Nd), and deposition occurred in local and regional sinks, creating the smooth material (Ns). The dissected unit (Nd) likely was once more geographically extensive, but intense erosion led to slope retreat and peneplanation, leaving the smooth depositional material (Ns) in its place. The high relief (~1 km) between inliers and adjacent smooth material implies that local deposition could not account for the vast amount of material eroded. Instead, a majority of the sediment was likely transported downslope to the Tharsis trough, then under control of the pole-to-pole slope carried northeast, out of the mapped region, and into the northern plains. Assuming that the inliers were originally part of the topographically high plateau to the east and grossly represent the original surface elevation, we estimate that 1.5×10^6 km^3 of high-standing Noachian plateau was removed from the study area and redeposited in topographically lower sinks to the north. Evidence for this wide-scale process includes: (1) the presence of topographically high, early and middle Noachian inliers scattered throughout the terrain (Figs. 1, 2, and 3), (2) a break in slope consistent with the edge of the Noachian plateau materials (Fig. 1), (3) the cessation of many valley networks at the topographically low,

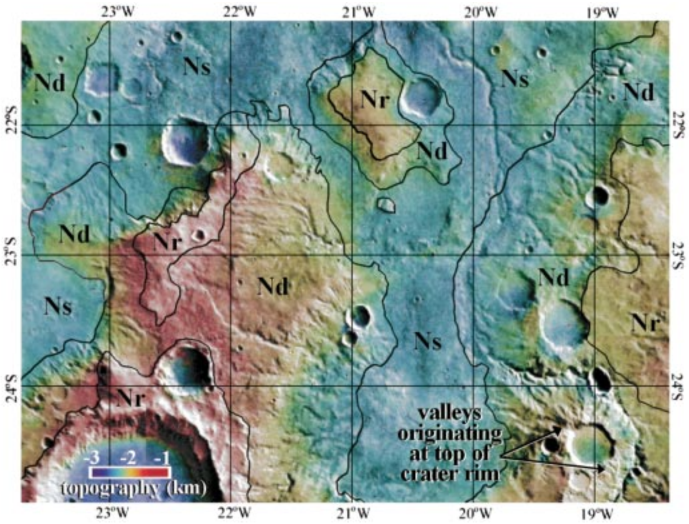

Figure 3. Viking-based Mars digital image mosaic of part of Margaritifer Sinus region illustrating key geomorphic units and their mapped contacts. Subtle fine-scale topography is overlain to highlight stratigraphic relations. Entire geomorphic map is presented in Figure 2. Contacts between rough (Nr), dissected (Nd), and smooth (Ns) materials are included. Note valleys originating at tops of crater rims, suggestive of surface runoff. Degraded rough material (Nr) coincides with large craters and occupies topographically highest reaches of area. Dissected material (Nd) occurs on areas of high gradient and contains numerous dense valley systems, many of which terminate at unit Ns. Smooth material (Ns) fills lowest areas of image and exhibits few craters, valley networks, or variations in topography.

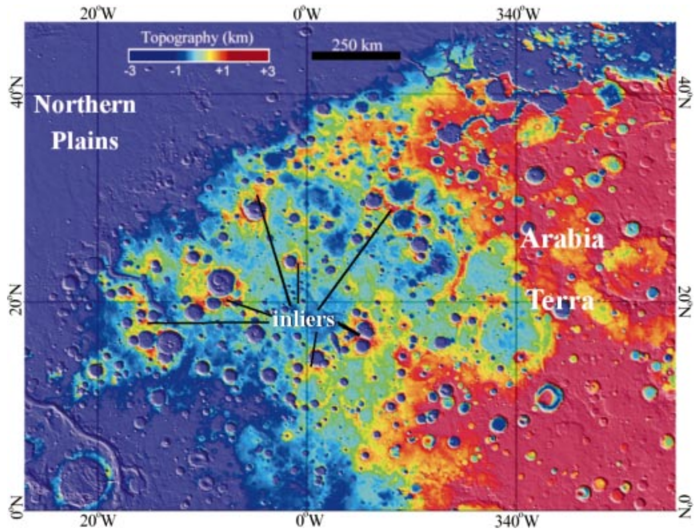

Figure 4. Mars Orbiter laser altimeter–generated shaded relief image of western Arabia Terra. Typical highland terrain is seen in orange to east. Many topographically high, heavily cratered inliers (examples indicated) are observed in central part of figure, surrounded by lightly cratered, smooth terrain (seen in shades of blue). Northern plains occupy topographically lowest region in image, northwest of degraded uplands. Pole-to-pole topographic slope has been removed in data (Smith et al., 1999) to stress regional differences in relief.

smooth depositional material (Ns) (Figs. 2 and 3), and (4) high drainage densities and valley order (fourth to fifth) seen in parts of the mapped region (Fig. 3).

There is evidence for a large paleolake in the region (Parana basin; 22.5°S, 12.5°W, area ~33 000 km^2) (Goldspiel and Squyres, 1991). The depression contains hummocky interior deposits with interspersed smooth terrain (Ni) that were emplaced contemporaneously with the extensive denudation and valley network formation. A large number of valley systems terminating at the proposed shoreline of Parana basin are believed to have been sources for the paleolake (Goldspiel and Squyres, 1991). The unit HNl contains a hematite spectral signature and is interpreted to be sedimentary layers deposited from large-scale water interactions (Christensen et al., 2000).

Modification of the mapped part of the Tharsis trough (Figs. 1 and 2) took place near the end of, or shortly after, denudation, when floodwaters from beyond the mapped region are believed to have eroded the trough and carried sediment into the northern plains (Parker et al., 2000). The floods likely aided the transportation of large amounts of sediment that had accumulated within the Tharsis trough during the period of denudation.

TIMING AND CESSATION OF RESURFACING

Cumulative crater counts at specific diameters have been used to define Martian geologic epochs, but conversion to absolute age depends on models of impact flux. Crater counts (following method of Tanaka, 1986) combined with superposition and crosscutting relationships from mapping were used to determine the sequence and timing of events. Total crater densities as well as superposed crater densities were calculated for each geomorphic unit to give a relative age and a younger limit of relative age, respectively. We did not date the age of formation of all geologic units; rather, crater densities on geomorphic units date the time and duration of the surface-modifying event. The dissected terrain (Nd) and topographically lower smooth material (Ns), which is likely sedimentary deposits derived from local peneplanation, formed in the late Noachian. These geomorphic units are representative of the period of intense erosion, thereby limiting the timing of that event to the late Noachian, consistent with previous work in the Margaritifer Sinus region (Craddock et al., 1997).

Applying the absolute age models of Neukum and Wise (1976) and Hartmann et al. (1981) (in conjunction with the classification scheme of Tanaka, 1986) provides estimates of the late Noachian interval of 500 m.y. and 350 m.y., respectively (the end of the Noachian Epoch occurs at 3.8 Ga and 3.5 Ga with these models). Using these values and our determination of the amount of material removed, we estimate an average denudation rate of 2.0 μm/yr and 2.9 μm/yr from the two age models. These rates are similar to previous estimates in the cratered uplands (Craddock and Maxwell, 1993) and are equivalent to low-end denudation rates of typical slopes in temperate maritime climates on Earth (Saunders and Young, 1983). We believe these numbers to be minimum rates of denudation because we have assumed a continuous process and also have not accounted for any subsequent infill from eolian, volcanic, or mass-wasting processes.

ADDITIONAL EVIDENCE FOR EXTENSIVE EROSION IN THE CRATERED UPLANDS

Examination of the MOLA data indicates that the evidence of denudation in Margaritifer Sinus likely extends to the north, throughout much of western Arabia Terra (0°–40°N, 25°W eastward across the prime meridian to 330°W). This region is a heavily degraded landscape hosting numerous inliers with large rugged craters, suggesting that these are remnants of a very old surface (Fig. 4). The intervening areas contain a few vaguely defined channels and terrain that is nondescript in the MOLA topography, geomorphically similar to the smooth material (Ns) in the mapped region. Carr (1996) noted a lack of valley networks in western Arabia Terra, atypical of the cratered uplands. Drawing on our observations in the Margaritifer Sinus region, we suggest that valley networks formed and then were subsequently removed in western Arabia Terra. This area is anomalously low compared to typical highland terrain (Smith et al., 1999); thus lack of dissected material (Nd) may indicate a higher degree of erosion than seen in Margaritifer Sinus region, resulting in the peneplanation of western Arabia Terra. Furthermore, gravity and topography data from Mars Global Surveyor mission indicate that western Arabia Terra has unusually thin crust when compared to other highland terrain (Zuber et al., 2000). Invoking massive denudation would explain the lack of valley networks, low elevation, and unusually thin crust (an isostatic response to peneplanation) observed in this region of the Martian highlands.

The volume of material removed from western Arabia Terra can be estimated using fine-scale MOLA grids if the inliers are representative of the original surface elevation, analogous to the method used in the Margaritifer Sinus region. The contribution of 3×10^6 km^3 of material from western Arabia Terra combined with our estimate of material removed from the Margaritifer Sinus area results in a total of 4.5×10^6 km^3 of early and middle Noachian cratered terrain that has been stripped from the examined area, and presumably transported out of the highlands and deposited in the plains. This volume would deposit a uniform 120-m-thick layer of sediment on the Martian surface north of 30°N.

POTENTIAL MECHANISM OF RESURFACING

Our local geomorphic mapping and regional examination of topography, images, and valley network distribution provide clear evidence of widespread landscape denudation. The geomorphic agent most capable of such widespread denudation and transportation of upland materials is running water. We envisage a scenario similar to the model that Craddock and Maxwell (1993) developed to explain crater degradation in the highlands. After the emplacement of the cratered uplands, a period or periods of precipitation began the process of erosion. Sheetwash gave way to valley incision on steeper slopes. These high-gradient areas were preferentially eroded, and deposition occurred in topographically lower areas. As this process continued, slope retreat formed isolated massifs with dissected slopes (Nd) and intervening peneplaned regions (Ns), consisting of sediment derived from local sources as well as sediments transported from up-gradient valley networks on unit Nd. Abundant inliers, valley networks, evidence for paleolakes, the hematite locale, and flood deposits are all consistent with existence of surface and near-surface water.

SUMMARY

Our geomorphic mapping has revealed several important events that shaped the present-day landscape in one part of Mars. Unless earlier valley networks have been completely destroyed, valley network formation in the Margaritifer Sinus region began near the middle-late Noachian boundary and continued to the end of the Noachian, a very restricted interval of time. The late Noachian was a time of massive erosion, possibly induced by precipitation, that removed substantial parts of the cratered uplands and any superposed valley networks. Much of the eroded sediment may have been carried off the margins of the Arabia bulge, through the Tharsis trough, and into the northern plains. For precipitation and surface runoff to occur, the climate of Mars must have been drastically different from that of today.

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