JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E10, 5081, doi:10.1029/2002JE001842, 2002

Amazonis Planitia: The role of geologically recent volcanism and sedimentation in the formation of the smoothest plains on Mars

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Received 10 January 2002; revised 19 March 2002; accepted 5 June 2002; published 22 October 2002.

[1] Amazonis Planitia, located between the two main volcanic provinces on Mars (Tharsis and Elysium), is characterized by extremely smooth topography at several scale lengths, as smooth as oceanic abyssal plains topography on Earth. We use Mars Global Surveyor (MGS) data (primarily very high resolution Mars Orbiter Laser Altimeter (MOLA) topography and derivative slope maps, gradient maps, and detrended maps) to examine the surface morphology of Amazonis Planitia and the stratigraphic relationships among previously mapped and newly defined units. These new data reveal the presence of a 1300 km diameter Noachian impact basin in northwest Amazonis Planitia and an extensive Late Hesperian lava flow unit that appears to have originated from the Olympus Mons source area prior to aureole formation. The presence of this previously unrecognized flow unit strongly suggests that Olympus Mons activity dates back to at least the Hesperian, as did activity on the Tharsis Montes. Emplacement of this ~100 meter thick flow unit formed a barrier along the northern margin of Amazonis Planitia which had a profound influence on the subsequent geologic history of the region. Formation of Olympus Mons aureole deposits created an eastern topographic barrier, and subsequent Tharsis Montes lava flows entered the basin from the south, flowing around the aureole. These three barriers (degraded Noachian crater rim, proto-Olympus Mons flow unit, and Olympus Mons aureole) caused subsequent lava flows and outflow channel effluents, primarily from the Elysium region to the west, to pond on the floor of Amazonis Planitia, preferentially smoothing the terrain there. Mars Orbiter Camera (MOC) images substantiate that at least two very fluid lava flows alternated with fluvial episodes from Elysium Planitia, flowing through Marte Valles onto the floor of the Amazonis Planitia basin. Within Amazonis Planitia, MOC images show flow-like textures heavily mantled by sediments, and radar data reveal the presence of rough lava flow surfaces underlying the sedimentary debris. These data thus suggest that the unique smoothness of Amazonis Planitia is the result of deposition of thin fluid lava flows and fluvial sediments in an enclosed basin. Crater counts suggest that the most recent resurfacing may have occurred in the latest Amazonian Period, in the last 1% of the history of Mars. In light of its unique history, it is somewhat ironic to note that Amazonis Planitia was originally thought to be a typical young Martian surface and therefore used to name the Amazonian era. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars; 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5470 Planetology: Solid Surface Planets: Surface materials and properties; 5480 Planetology: Solid Surface Planets: Volcanism (8450); 4267 Oceanography: General: Paleoceanography; *KEYWORDS:* Mars, water, Amazonis Planitia, Marte Vallis, volcanism, Amazonian

Citation: Fuller, E. R., and J. W. Head III, Amazonis Planitia: The role of geologically recent volcanism and sedimentation in the formation of the smoothest plains on Mars, *J. Geophys. Res.*, *107*(E10), 5081, doi:10.1029/2002JE001842, 2002.

1. Introduction

[2] Amazonis Planitia (Figure 1) is of extreme interest in terms of the geological history of Mars as the location of persistent volcanic and outflow channel deposition, including some of the youngest fluvial deposits and lava flows on the planet [*Scott and Tanaka*, 1986] (Figures 2 and 3). Remote sensing data have shown that Amazonis Planitia contains some of the smoothest deposits yet detected in the Solar System [*Aharonson et al.*, 1998, 2001; *Kreslavsky and Head*, 1999, 2000] and units with radar backscatter properties suggestive of young volcanism [*Harmon et al.*, 1999]. In this analysis, we use MGS data

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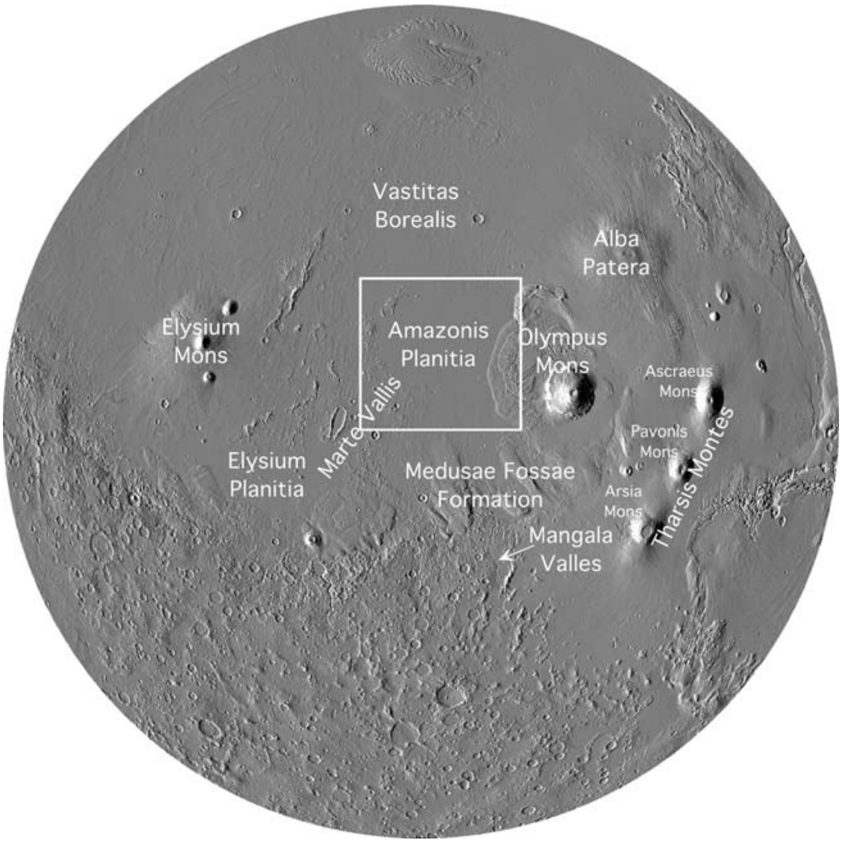


Figure 1. Regional context map showing Amazonis Planitia and surrounding geologic features: major volcanic edifices (Mons and Montes); Mangala Valles, a set of outflow channels; Marte Valles, a volcanically resurfaced outflow channel; Elysium Planitia, a volcanic plain and the site of the Cerberus Formation volcanism; the Vastitas Borealis, the subpolar lowlands; the Medusae Fossae Formation, an extensive, friable unit whose origins are under debate [cf. *Zimbelman et al.*, 1999] but appear to be an air fall ash deposit [*Bradley et al.*, 2002]. Map is a hemispheric, Lambert equal-area projection, MOLA-derived gradient map centered at 15°N, 165°W.

to characterize the geology of Amazonis Planitia, to reexamine stratigraphic units and their sequence, and to address the reasons for its extreme smoothness (Figures 3–7). We find that early Tharsis-radial lava flows of likely Late Hesperian age created a barrier across northern Amazonis Planitia that heavily influenced its later history, forming a shallow basin that trapped lava flows and outflow channel effluents. Subsequent lava flow and outflow channel emplacement events during the Hesperian and Amazonian repeatedly resurfaced Amazonis Planitia, contributing to its extreme smoothness. This activity has continued until geologically very recently.

2. Background

2.1. Geography

[3] Amazonis Planitia is located between Tharsis and Elysium, at approximately 140–175°W, 15–45°N (Figure 1). It is a topographically low region approximately 1300 by 900 kilometers in area (halfway in total area between Texas and Alaska, or about one-third the size of western Europe) that is dominated by smooth topography showing no measurable roughness at kilometer scales. This smooth area correlates approximately with unit Aa_3 of *Scott and Tanaka* [1986], the middle member of their Arcadia Formation, and is contiguous with the Cerberus Formation of *Plescia* [1990] (Figure 2).

2.2. Geological Mapping

[4] The 1:15 million scale maps, text, and correlation charts of *Scott and Tanaka* [1986] and *Greeley and Guest* [1987] (Figures 2 and 3) summarize the geological history of Amazonis Planitia on the basis of Viking data; this section reviews their findings. During the Noachian, heavy bombardment and volcanic resurfacing reshaped the initial crust and the dichotomy boundary was formed. South of the dichotomy, Noachian-aged terrain is widespread, exposed primarily as heavily cratered plains. North of the boundary, Noachian-aged outcrops are rare, limited to degraded knobs mantled or embayed by younger terrain. Recent Mars Orbiter Laser Altimeter (MOLA) analysis also suggests the presence of numerous modified and buried Noachian craters in the northern lowlands [*Frey et al.*, 2001]. Amazonis Planitia is located north of the dichotomy boundary; the exact character of the boundary zone in this region is unclear, as the extension of the scarp is largely buried beneath the Medusae Fossae Formation [*Scott and Tanaka*, 1986; *Greeley and Guest*, 1987]. Nonetheless, the boundary

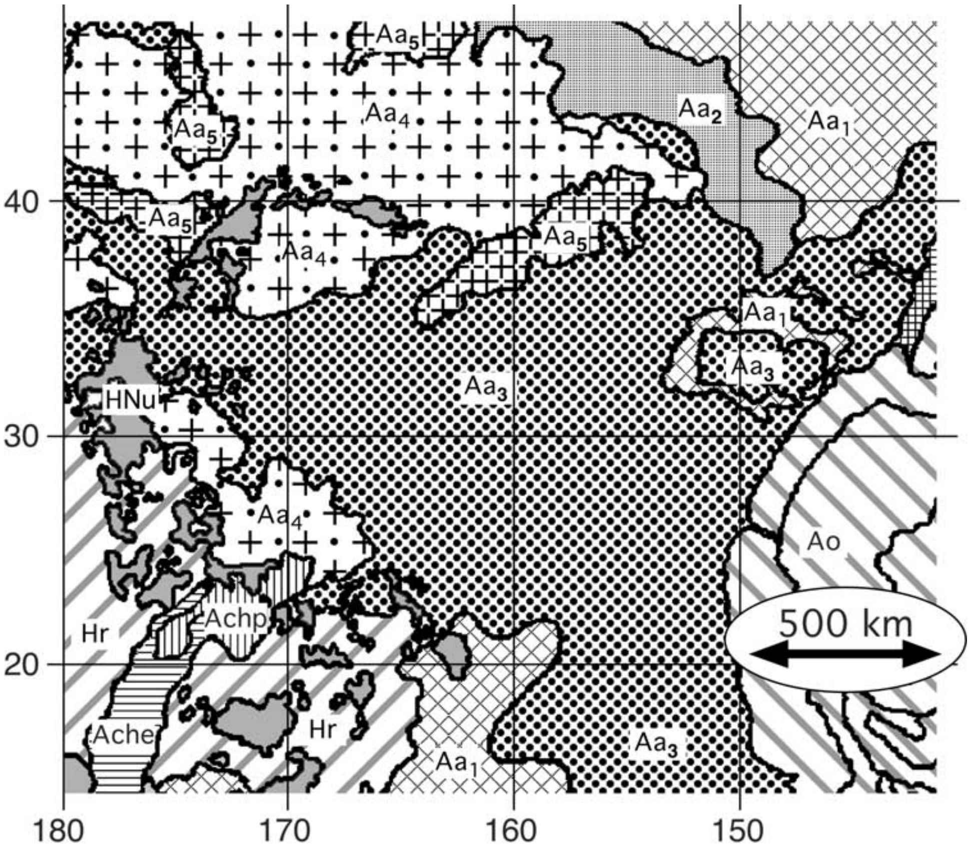


Figure 2. Generalized geologic map of Amazonis Planitia, after *Scott and Tanaka* [1986]. Units referred to in the text are labeled. Nf, on the eastern margin, is a tip of the Noachian Acheron Fossae. HNu, undifferentiated material of the Hesperian and/or Noachian era, forms an arc in the western part of the region. Hr, Hesperian-aged wrinkle ridges, are visible in the southwest. Ao includes all Olympus Mons aureole members. Aa_1-Aa_5 are members of the Arcadia Formation, an Amazonian volcanic suite. Ache and Achp, visible in the southwest corner, are the channel deposits and outwash plain of the Upper Amazonian Marte Valles outflow. 140°–180°W, 10°–40°N, north at the top.

here appears to be a distinctive topographic break up to 2–3 kilometers in elevation above the northern lowlands.

[5] Hesperian-aged units show evidence of outflow channel activity, tectonism, and extensive volcanism. In Amazonis Planitia, Lower Hesperian volcanic plains (Hr) were emplaced and subsequently deformed by wrinkle ridges. In the Late Hesperian, outflow channels carved the Mangala Valles to the south; to the north, the Vastitas Borealis Formation was emplaced in the majority of the northern lowlands [*Scott and Tanaka*, 1986; *Greeley and Guest*, 1987; *Tanaka and Scott*, 1987]. Flows from Alba Patera (Hal) and from the Tharsis Montes (Ht_{1-2}) may have also influenced Amazonis Planitia.

[6] The Amazonian Period was marked by extensive effusive volcanism from Olympus Mons and the volcanoes of the Tharsis Montes (Tharsis Montes Formation), and the waning stages of volcanism from Alba Patera (Figure 3). For the Amazonis Planitia region, the most important Amazonian events were the Olympus Mons aureole emplacement to the east (the Olympus Mons Formation, Aoa_{1-4}), Elysium Planitia channel activity to the southwest, and emplacement of the Arcadia Formation (Aa_{1-5}). In addition, the Medusae Fossae Formation was emplaced along the dichotomy boundary just to the south of Amazonis Planitia. The presence of unconformities between the subunits of the Medusae Fossae Formation [e.g., *Scott and Tanaka*, 1986; *Greeley and Guest*, 1987; *Sakimoto et al.*, 1999] suggests that it may have once been more widespread than it is at present.

[7] Studies published subsequent to the 1:15,000,000-scale global maps offered various reinterpretations of the Arcadia Formation and the Amazonis Planitia region. *Plescia* [1990] and *Scott and Chapman* [1991] examined Viking images of Elysium Planitia and came to opposite conclusions. *Plescia* [1990] interpreted the region as volcanically resurfaced, resulting from one or more low-viscosity (probably basaltic) volcanic flooding events. He argued that the lava first pooled in a regional low within Elysium Basin, then moved eastward through the previously carved channels within Marte Valles, then spread laterally into Amazonis Planitia, terminating in digitate lobes. He tentatively proposed that the fluvial and volcanic activities were related, suggesting that the channels might have been initially carved by a catastrophic flood that resulted from the melting of ground ice by magma intruding into the region [*Plescia*, 1990].

[8] *Scott and Chapman* [1991] interpreted Elysium Basin to be a large lake or inland sea which overflowed through Marte Valles into Amazonis Planitia. They acknowledged

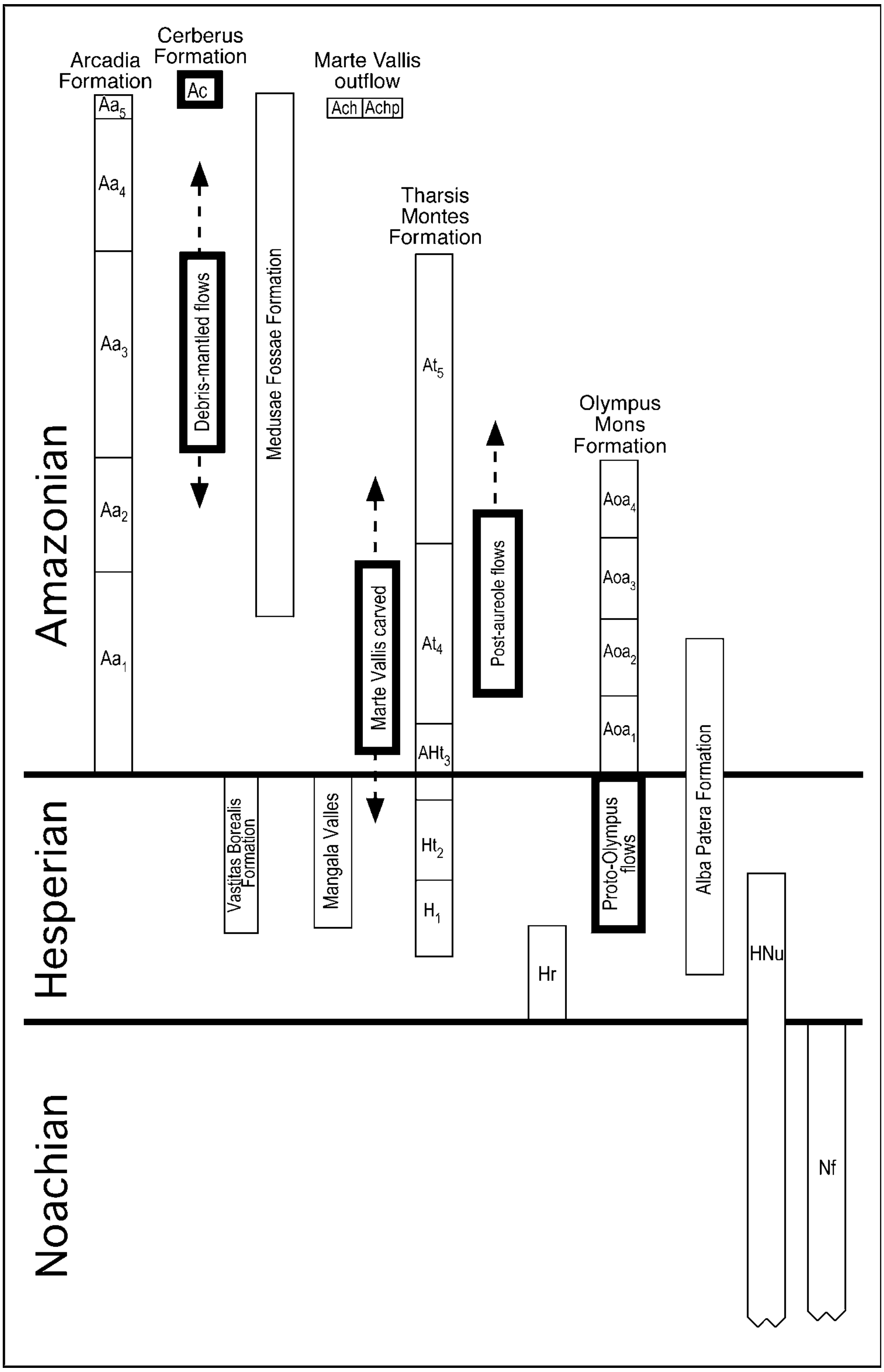


Figure 3. Stratigraphy of the units present in the study area, after *Scott and Tanaka* [1986]. Units not identified in their stratigraphy are highlighted. Aa_1-Aa_5 are members of the volcanic Arcadia Formation, all of which have been reinterpreted in this study. The Cerberus Formation, unit Ac, was first mapped by *Plescia* [1990]; the geometry of the northeastern distal portion is refined in this study. The Amazonian debris-mantled flows entered Amazonis Planitia through Marte Valles and are visible in radar data (cf. Figure 8). The post-aureole flows curve around the southeastern boundary of the Olympus Mons aureole and likely originate from Tharsis. The proto-Olympus flows predate the emplacement of the Olympus Mons aureole (units Aoa_{1-4}) and extend WNW from Olympus Mons across northern Amazonis Planitia. All units discussed in text.

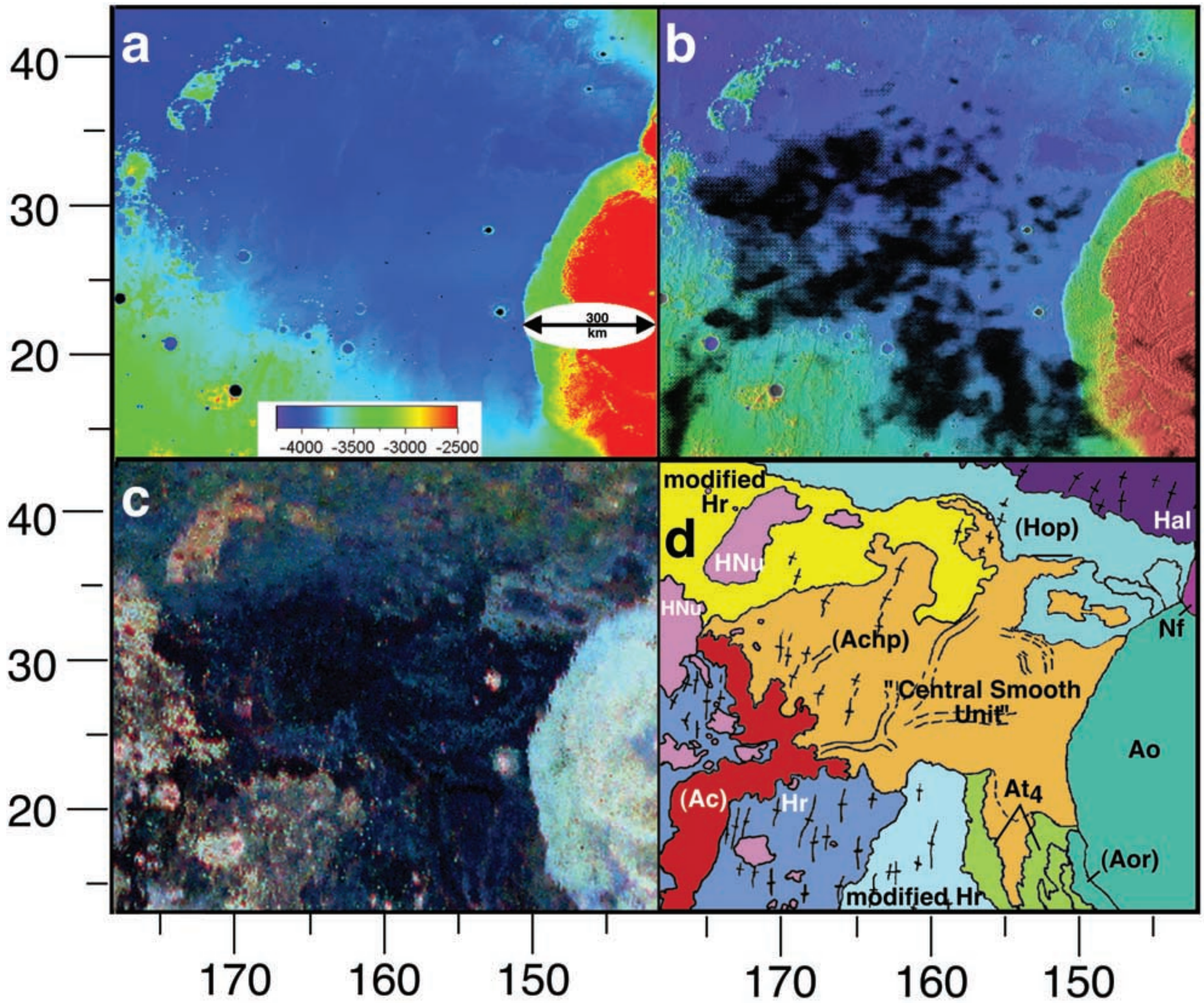


Figure 4. Data from the Amazonis Planitia region. (a) A digital elevation model from gridded MOLA altimetry data; generated from all MOLA profiles taken in Amazonis Planitia, this DEM has a resolution higher than the 32 $\times$ 64 gridded data set. (b) DEM from (a), overlain on a MOLA-derived gradient map (see Figure 5b), with radar data after *Harmon et al.* [1999], collected with the Arecibo 12.6-cm wavelength telescope in December 1990 and 1992. Dark regions represent areas of strong backscatter due to decimeter-scale surface roughness, which *Harmon et al.* [1999] found corresponds to young lava flows. (c) MOLA-derived surface roughness map [from *Kreslavsky and Head*, 2000], generated by applying color values to roughness at three scales: 0.6 km (blue), 2.4 km (green), and 19.2 km (red); bright areas are rough at multiple wavelengths, dark areas smooth at multiple wavelengths. The central smooth unit of Amazonis Planitia is virtually black, signifying an almost complete lack of roughness at all kilometer-scale wavelengths. (d) New geologic sketch map of the Amazonis Planitia region, showing earlier units shown by letters (see Figure 2) and newly identified units (shown by USGS-style letters in parentheses): (Hop) proto-Olympus Mons flow unit; (Aor) runoff from the Olympus Mons aureole; (At_4) post-aureole Tharsis flows; modified volcanic plains (modified Hr); (Achp) outwash plains from Marte Valles outflow events, corresponding to the ''central smooth unit'' described in the text; (Ac) Cerberus Plains flow unit. 142°–178°W, 13°–43°, north at the top.

the presence of lava flows, but argued that fluvial activity postdated volcanic activity on the basis of surface features that they interpreted as terraces and scour marks or ''etching'' of underlying lava [*Scott and Chapman*, 1991].

[9] *Parker et al.* [1993] drew Contact 2, one of two interpreted shorelines for their proposed Hesperian northern ocean, near the margins of the central smooth unit of Amazonis Planitia. *Head et al.* [1999], using MOLA data, assessed the elevation of the two contacts, and found that Contact 1 deviated substantially from an equipotential line, but that Contact 2 was much closer to being level, with a mean elevation of 3760 m below the Martian datum. Figure 5e shows the trace of the −3760 m contour through the Amazonis Planitia region.

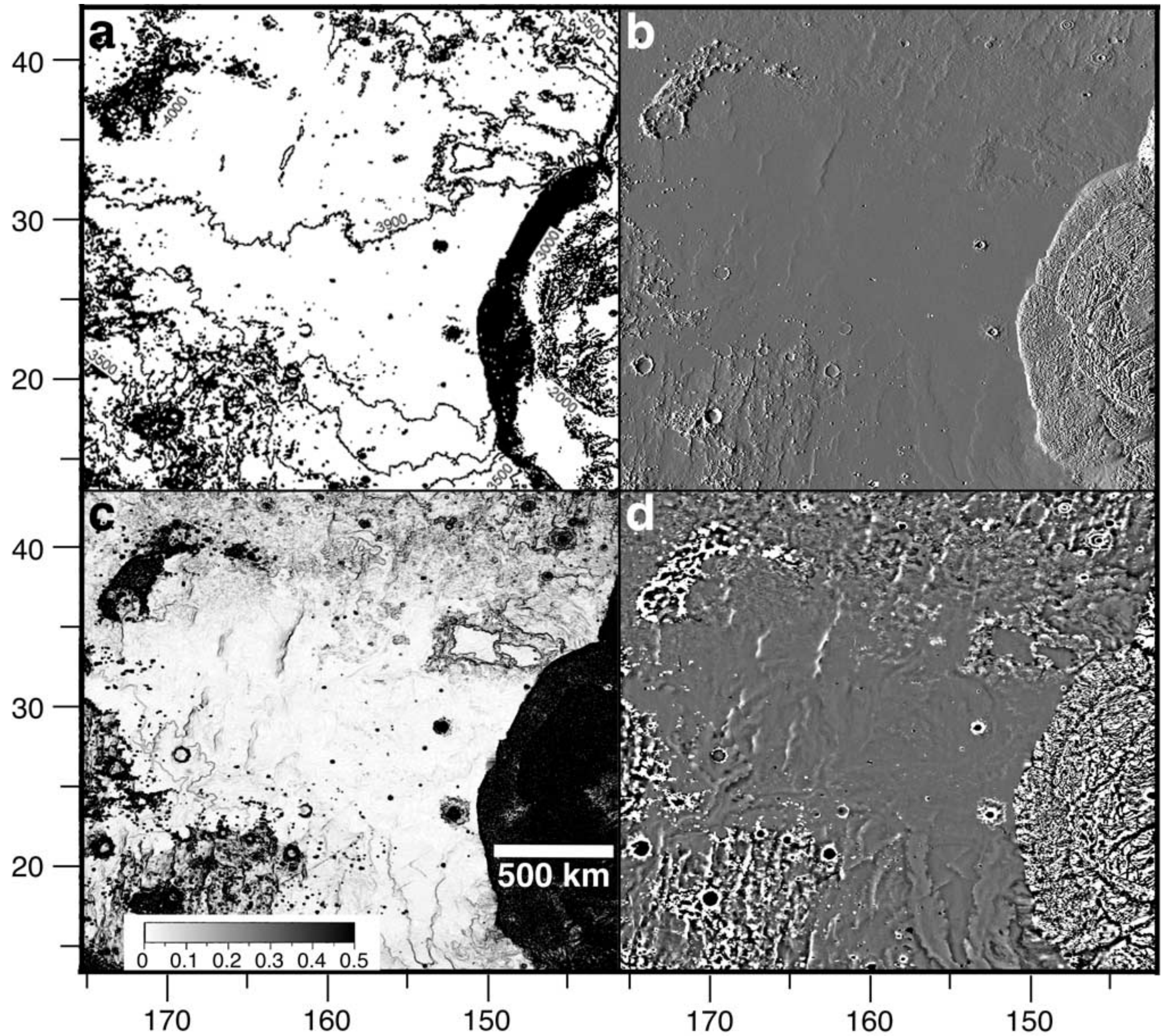


Figure 5. MOLA data from the Amazonis Planitia region. (a) Contour map of the Amazonis Planitia region, highlighting the regional S-N slope and the smoothness of the central plain. Contour interval is 100 meters. Note also the contours in the NE corner, showing the Alba Patera rise. (b) Gradient map showing local variations in elevation; illumination is from the west (left). (c) Slope map, with scale stretched such that all areas with slope steeper than 0.5° are completely black. Note the digitate distal boundaries of the youngest volcanism (red in Figure 4d) and the complete lack of slope in the central plain (see also Figure 10). (d) Detrended MOLA data; after removing local slope, local relief stands out sharply. For detailed discussion of detrending, see *Kreslavsky and Head* [1999] and *Head et al.* [2002]. Note the wrinkle ridges protruding through the otherwise smooth central unit; the wrinkle ridges can be seen to be part of the system of ridges visible in Hr to the south and the volcanic plains to the north [*Head et al.*, 2002]. (e) The contour representing −3760 km is overlain on the gradient map (142°–195°W, 13°–43°N). *Head et al.* [1999] found that −3760 km was the average elevation of Contact 2, proposed by *Parker et al.* [1989, 1993] to be a shoreline for a northern ocean. If filled to this line by a northern ocean, Amazonis Planitia would have been submerged to a depth of approximately 200 m, for a total water volume of approximately 2×10^5 km^3 in the area shown. Parts a–d: 142°–178°W, 13°–43°, north is at the top.

[10] *Morris and Tanaka* [1994] mapped the eastern edge of Amazonis Planitia in their analysis of the Olympus Mons region. They identified two plains subunits of the Arcadia Formation (Figure 2): Aa_1 and Aa_2, both volcanic plains mantled by aeolian deposits. They also present evidence that the age of mapped volcanic units associated with Olympus Mons span the Middle to Late Amazonian, and that if the aureole deposits represent the collapse of a proto-Olympus Mons edifice, then extrusive activity must have extended back to the Late Hesperian. On the basis of their mapping,

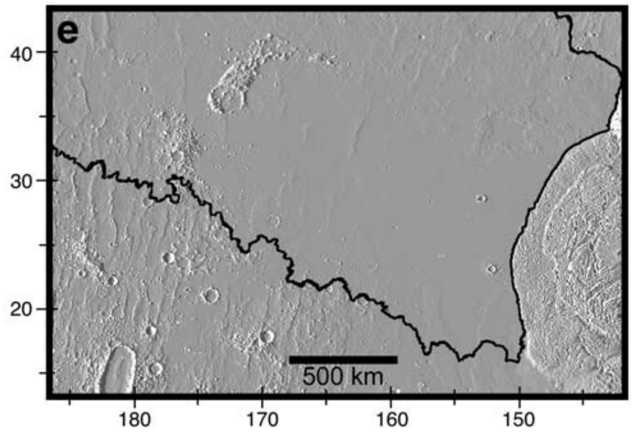


Figure 5. (continued)

they favor a landsliding and gravity-spreading mechanism [see also *Tanaka*, 1985; *Francis and Wadge*, 1983], but point out that this requires a lubricant such as water or ice. They further point out a weakness of their hypothesis: "if a huge, proto-Olympus Mons had formed (necessary for the landsliding and gravity-spreading mechanisms), extant lava flow fields beyond the aureoles might be expected, but they are absent" [*Morris and Tanaka*, 1994, p. 15].

2.3. Earth-Based Radar Studies

[11] Earth-based radar studies provided important information on the nature of Amazonis Planitia and the relations of units there to those in Elysium Planitia and Marte Valles (Figure 7). *Harmon et al.* [1992, 1999] used delay-Doppler mapping at Arecibo to identify regions of high decimeter-scale roughness on Mars, and found a strong correlation between radar-bright regions and young volcanism. They noted that Marte Valles is the only outflow channel with a strong radar signature [*Harmon et al.*, 1999], and that Elysium Planitia and Marte Valles surfaces provide some of the strongest radar backscatter signatures on Mars [*Harmon et al.*, 1992, 1999]. The signature within Amazonis Planitia is somewhat weaker than that of Elysium Planitia, but is still comparable to other areas of young volcanism [*Harmon et al.*, 1999].

2.4. Thermal Inertia Studies

[12] The Viking infrared thermal mapping experiment (IRTM) provided global information on the thermal inertia of the surface [*Kieffer et al.*, 1977; *Christensen*, 1982, 1986a, 1986b, 1988; *Christensen and Moore*, 1992, Figure 48]. These data show that the Amazonis region is in the western part of the largest of three major low-inertia regions on Mars. These regions are characterized by thermal inertias between 83 and 125 J m^{-2} $s^{-1/2}$ K^{-1} ($2-3 \times 10^{-3}$ cal cm^{-2} $s^{-1/2}$ K^{-1}), which imply a cover of dust particles ~40 μm in diameter or smaller. The very uniform thermophysical properties over the entire extent of these three regions and their relatively sharp boundaries, which do not correspond well to bedrock geologic unit boundaries, have been cited as evidence that these units are surface accumulations of fine dust [e.g., *Christensen*, 1986a]. Data from the MGS thermal emission spectrometer (TES) show that the regional thermal inertia values are essentially the same 21 years after Viking [*Jakosky et al.*, 2000].

2.5. Previous MOLA-Based Studies

[13] In previous studies, volcanic resurfacing, and aqueous and aeolian processes have been proposed as possible explanations for the extreme smoothness of the central

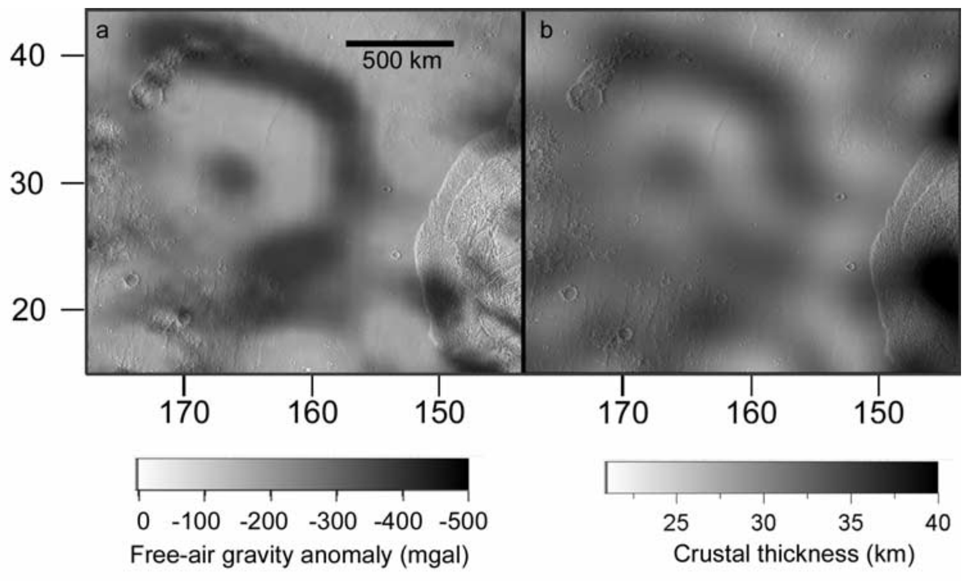


Figure 6. (a) Free-air gravity anomaly map, left [after *Smith et al.*, 1999a], and (b) crustal thickness model, right [after *Zuber et al.*, 2000], overlain on a Mola-derived gradient map of Amazonis Planitia. Note the bulls-eye pattern, typical of large impact basins. The relative gravity difference between the interior positive anomaly and rim negative anomaly is approximately 200 mGals (2×10^3 g.u.). 140°–180°W, 15°–45°, north is at the top. Reprinted with permission; copyright 1999 American Association for the Advancement of Science.

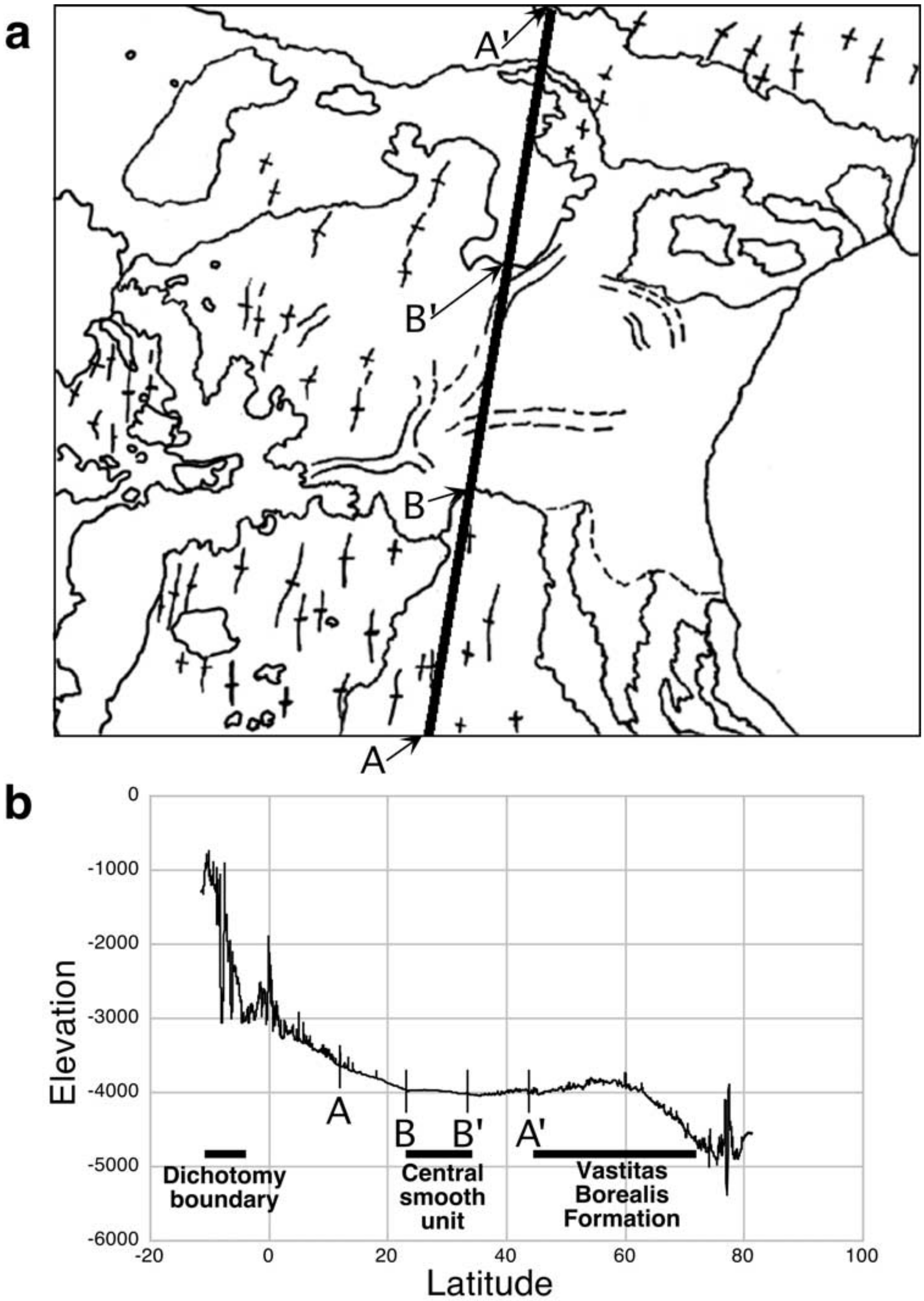


Figure 7. Smoothness of Amazonis Planitia. (a) Track of MOLA Pass 31 across the sketch map of Amazonis Planitia (cf. Figure 4d). A and A′ mark the boundaries of the map area, B and B′ the boundaries of the central smooth unit. (b) Profile of MOLA Pass 31, which drew initial attention to the smoothness of Amazonis Planitia [*Aharonson et al.*, 1998]; north is to the right. The dichotomy boundary can be seen, as can the extreme smoothness of the central smooth unit. The profile stretches north across the Vastitas Borealis Formation, which shows its trademark 2.4 km-periodicity roughness [*Kreslavsky and Head*, 1999, 2000; *Head et al.*, 2002]. Vertical exaggeration ~800×.

smooth unit. This unusual lack of surface roughness drew early attention from MOLA researchers. *Aharonson et al.* [1998] compared an early MOLA track (Pass 31) across Amazonis Planitia and the Vastitas Borealis Formation to profiles taken on other terrestrial planets, and found that the Martian plains were remarkable in their smoothness. The Amazonis Planitia-Vastitas Borealis track was dramatically smoother than Niobe Planitia on Venus or Oceanus Procellarum on the Moon, and three times smoother than even the Sahara desert [*Aharonson et al.*, 1998]. Its smoothness is comparable only with Earth regions shaped by long-term aqueous deposition, such as ocean floors and the North

American Great Plains (the former location of an epeiric sea) [*Aharonson et al.*, 1998]. Re-examination of Pass 31 shows that the smoothest region within the several thousand kilometer-long track corresponds precisely with the central smooth unit of Amazonis Planitia identified in this study (Figure 7).

[14] Using a 16 × 32 pixel/degree gridded global topography data set, *Kreslavsky and Head* [2000] created global surface roughness maps by assigning color values to roughness at three scales: 0.6 km (blue), 2.4 km (green), and 19.2 km (red) (Figure 4c). Due to the additive properties of color, the brightest areas were those that were rough at many wavelengths; the smoother terrain was darker. The brightest (roughest) terrain tended to be in the southern highlands, and the darkest (smoothest) areas on the map were found in Elysium Basin, Marte Valles, and Amazonis Planitia. These areas are a dark blue-black, reflecting an almost complete lack of roughness at any wavelength except the shortest (0.6 km, represented by blue), further underlining the uniqueness of the Amazonis Planitia area.

2.6. Previous MOC-Based Studies

[15] *Keszthelyi et al.* [2000] studied MOC images and modeled the Marte Valles lava flows. MOC images confirmed the *Plescia* [1990] hypothesis that volcanic activity had resurfaced the valley; *Keszthelyi et al.* [2000] saw lobate ridges, pressure ridges, rafted crustal slabs, ponded areas, and squeeze-ups. Their lava flow models, which they cautioned were accurate only to within a factor of 2, showed that the lava must have been basaltic; an ultramafic flow could not have created a crust thick enough to have formed the rafted textures visible in the images, and a basaltic andesite or more felsic material would have formed flows ~60 m thick, thicker than the 10 m thick flows *Plescia* [1990] had measured.

[16] It is noteworthy, however, that MOLA data reveal Marte Valles flows to have distal thicknesses of 20–40 m: the lobate toes stand at altitudes between −3823 to −3833 m above a floor between −3855 and −3865 m in elevation. These distal thicknesses may be an effect of inflation or piling up of flows, but if they reflect actual flow thicknesses, the modeled basaltic andesite thickness is within the *Keszthelyi et al.* [2000] model's margin of error. It is difficult to measure within-channel flow thicknesses, because the flows rarely stand above the surrounding material. Two proposed explanations for this are 1) the flows left behind only a thin veneer of material [*Therkelsen et al.*, 2001] or 2) the bulk of the lava was emplaced as infilling within fluvial channels [*Plescia*, 1990]. The fact that the flow surfaces are often the very lowest part of a MOLA profile supports the latter theory, though both may contribute to the apparent lack of relief of the flows (see also discussion in section 4.1).

2.7. Summary and Key Questions Addressed by This Study

[17] In summary, analysis of the smoothest plains on Mars, in Amazonis Planitia and adjacent areas, has shown that a range of processes may have operated there and contributed to the smoothness, including volcanism, tectonism, impact cratering, oceanic sedimentation, fluvial deposition, and aeolian processes. In this analysis, we use Mars Global Surveyor data to address the following key questions about this important and unique region: Do MOC and MOLA data support the stratigraphy and history (Figures 2 and 3) proposed on the basis of Viking data? (sections 3.2 and 3.3) What specific processes caused the unusual smoothness of Amazonis Planitia (sections 3 and 4, summary in section 5)? Is there evidence for ice or liquid water in Amazonis Planitia, in the past or currently (section 5)? What is the temporal relationship of volcanism, outflow channels and ponding in the areas bordering Amazonis Planitia (i.e., Elysium Planitia and Marte Valles), and is there a genetic relationship (section 4.2)?

3. Mars Global Surveyor

[18] Mars Global Surveyor (MGS) has provided a remarkable new data set that has led to reassessment of Martian topography, morphology, gravity, and mineralogy [*Albee et al.*, 2001]. These data have enabled geologists to characterize surface units and determine unit relationships in ways that have considerably improved our understanding of the history of Mars. The Mars Orbiter Laser Altimeter (MOLA) experiment has provided the most accurate global topographic map of any planet in the solar system, allowing for a clear, quantitative understanding of features and their relationships [e.g., *Smith et al.*, 1999b]. Mars Orbiter Camera (MOC) images reveal detailed morphology at the meter to decameter scale and provide new information on the characteristics of geologic units and the processes that are modifying them [e.g., *Malin et al.*, 1998]. The Magnetometer/Electron Reflectometer (MAG/ER), measuring Mars' magnetic fields, has shown that there is no currently active magnetic dynamo, but that there was one in the distant geologic past [*Acuña et al.*, 1999], and that there are remnant magnetic anomalies today [*Purucker et al.*, 2000]. Precise measurements of the satellite position and planetary topography have led to the creation of detailed gravity models of the planet [*Smith et al.*, 1999a], providing a window to the crustal and lithospheric structure of Mars [*Smith et al.*, 1999a; *Zuber et al.*, 2000]. The Thermal Emission Spectrometer uses the thermal infrared energy emitted from Mars to analyze the mineralogy of the surface [e.g., *Christensen et al.*, 1998; *Bandfield et al.*, 2000] and assess the thermal inertia of surface materials [e.g., *Jakosky et al.*, 2000].

[19] This study uses new MGS data to characterize the nature of the surface in Amazonis Planitia and adjacent areas and to reassess the nature and sequence of geologic units. We focus on MOLA data, and present new maps of the surface (Figures 4 and 5) portrayed as color-coded altimetry maps, topographic contour maps, detrended topography maps, topographic gradient maps, and regional to local-scale slope maps. These maps are complemented with high-resolution MOC images that show the nature of units and their relationships (Figure 9). Finally, we present a new geologic sketch map synthesizing the relationships revealed by the new data (Figure 4d), and a series of paleogeographic sketch maps interpreting the sequence of geological events (Figure 11).

3.1. MGS Data Analysis

[20] The regional topography of Amazonis Planitia (Figures 4a, 5a, and 5b) shows a remarkably smooth central terrain flanked by high-relief units to the east (the Olympus

Mons aureole), the northeast (the tip of Acheron Fossae and the flanking slopes of Alba Patera), the northwest (remnants of arcuate outcrop of Hesperian-Noachain-aged terrain, HNu), and the southwest and south (the eastern margin of Elysium and the northern edge of Lucus Planum). Regional topography shows that the floor of Amazonis Planitia is very flat, tilts toward the north and north-northwest, and is topographically open in that direction, toward the northern lowlands. Topographic gradient maps (Figure 5b) and detrended topography maps (Figure 5d) confirm the presence of extensive wrinkle ridges that are superposed on the Hesperian ridged plains (Hr; Figure 2). The detailed detrended map (Figure 5d) permits the mapping of these structures into the northern lowlands and *Head et al.* [2002] have shown that they are pervasive there, underlying the Late Hesperian Vastitas Borealis Formation. It is also clear that these features trend across western Amazonis Planitia as part of a pervasive texture of ridges that are broadly circumferential to the Tharsis rise, and that they are progressively buried by younger units in central and eastern Amazonis (Figure 5d).

[21] Closer investigation reveals a variety of subtle textures that we use to identify, define, and map geologic units (Figures 4 and 5). Detrending the topographic data (Figure 5d) [*Head et al.*, 2002] reveals surface textures and roughness signatures which help to distinguish units; it also highlights locations of sharp topographic relief. For example, a series of prominent lobate flow-like features is now seen to enter Amazonis Planitia from the south, curving around the Olympus Mons aureole, and thus postdating it. Comparison of the roughness maps of *Kreslavsky and Head* [1999, 2000] (Figure 4c) and the detrended map suggest that these are lava flows that enter the basin but are truncated by superposed flow-like features extending in a west-east direction from the Marte Valles region. Detailed analysis of the detrended map (Figure 5d) also reveals the presence of a narrow zone of small lobes along the front of the Olympus Mons aureole, features suggesting that there may have been drainage or erosion from the oldest aureole facies (see Figure 9d), consistent with previous observations that it is more degraded than younger aureole deposits [e.g., *Morris and Tanaka*, 1994].

[22] We also generated slope maps with MOLA data, quantifying the terrain's steepness at any given location. The gradient map (Figure 5b) and slope map (Figures 5c, 10a) of Amazonis Planitia highlight the extreme smoothness of the central smooth unit, and the low relief of the entire region. In Figure 5c, the data has been stretched such that all areas with a slope steeper than 0.5° are completely black, to better illustrate the subtle slopes between 0–0.5°. Figure 10a shows a larger area, with an inverted scale. Figures 5c and 10a also show that the slope within Marte Valles is less than 0.1°. The slope maps (Figures 5c, 10a), together with the detrended topography (Figure 5d) and the roughness data (Figure 4c), can be used to identify and map lava flow boundaries (e.g., Figure 10b). Clearly visible are lobate boundaries of a flow unit (mapped in Figure 4d) extending WNW across the top of the map area from the base of the northern edge of the Olympus Mons aureole, and obscuring wrinkle ridges as it extends out over northern Amazonis Planitia for a distance of over 1500 km. This flow unit occurs in an area previously mapped as the Arcadia Formation, and includes parts of all of the subunits (Aa_1-Aa_5) [*Scott and Tanaka*, 1986] (Figure 2). The new data show that it is more likely to be dominated by a single major flow unit (Figure 4d), with several smaller lobate flow units along the eastern edge. The sharp contact between the aureole and what appear to be the proximal upslope parts of the flow units strongly suggests that this flow unit predates formation of the aureole. This aureole-flow contact, combined with the downslope direction of the flow unit, suggest that it originated in the vicinity of Olympus Mons. This flow may therefore represent evidence of the "extant lava flow fields beyond the aureoles" that *Morris and Tanaka* [1994] pointed out should be expected if the aureoles formed from collapse of a proto-Olympus Mons edifice, but which they did not see evidence for in Viking data.

[23] Also visible in these data are lobate flow and channel-like features and units that appear to enter Amazonis Planitia through Marte Valles (to the west), and extend in a west to east direction across the floor of the plains (Figures 4c and 5d). These same data show that these units overlie lava flow units from the Tharsis Montes that enter the basin from the south. All of these units appear to have been contained in Amazonis Planitia by the extensive lobate flow unit stretching across the northern margin of the map area.

3.2. Mapping

[24] MGS data thus allow us to extend and enhance the geologic mapping done on the basis of Viking data. The improved geomorphologic resolution from MOLA has revealed features (summarized in Figure 4d) whose gentle slopes and mild relief made them indistinct or invisible in Viking Orbiter data, such as post-aureole flows from southern Tharsis, with slopes on the order of a tenth of a degree, and the detailed channel textures visible within the smooth central unit. The improved topography data also provide a much more detailed three-dimensional look at the Martian surface, permitting analysis of complicated stratigraphic relationships to an unprecedented degree.

[25] The map produced from MGS data (Figure 4d) adds two major elements to the 1:15,000,000 scale map (Figure 2) [*Scott and Tanaka*, 1986]: 1) the Late Hesperian proto-Olympus Mons flow, which was not previously mapped and which cuts across the boundaries of units Aa_{1-5}; 2) the Amazonian post-aureole Tharsis flows, which are included in *Scott and Tanaka*'s [1986] unit Aa_3. We also reinterpret several units. Aa_3, the smooth central unit, mapped as a volcanic plain, is interpreted to be a complex sequence of sedimentary and volcanic units, which have also undergone aeolian modification. Ach/Achp, described as a fluvial channel and its outwash plain, is interpreted to be a channel carved by fluvial activity and volcanically resurfaced at least twice. The western outcropping of Aa_4 corresponds closely to the digitate distal lobes of the most recent Marte Valles lava flow event. The portion of Aa_1 mapped near the southern margin of the map area is reinterpreted to be an Hr surface modified by outwash from Mangala Valles. The outcrops of HNu, forming a large arc, are interpreted to be the remnant of an ancient impact crater.

3.3. Observations and Geologic History

[26] We now review the basic characteristics and geologic history of the region, based on these new MGS data

and interpretations and grounded in the previous 1:15,000,000 scale map [*Scott and Tanaka*, 1986].

3.3.1. Noachian

[27] The free-air gravity anomaly map of Mars [*Smith et al.*, 1999a] and the crustal thickness map of Mars [*Zuber et al.*, 2000] reveal a ~1300 km diameter, round feature in northwest Amazonis (Figure 6) consisting of a bulls-eye pattern with, moving outwards from the center, a negative gravity anomaly, a surrounding positive anomaly, and a ringing negative anomaly (Figure 6a).

[28] We have tentatively interpreted this anomalous region to be the trace of an ancient impact event (Figure 11a). The ~1300 km diameter anomaly is similar in scale to the Isidis impact basin [*Schultz and Frey*, 1990], which also shows a circular positive anomaly within a ringing negative anomaly [*Smith et al.*, 1999a]. The central positive anomaly in Isidis is significantly larger than that of this proposed impact basin; Isidis has a Δg (difference in gravity anomaly between the center and rim, following the convention of *Pilkington and Grieve* [1992]) of approximately 500 mGals, whereas the Δg of this basin is approximately 200 mGals. For comparison, Argyre Basin has a Δg of approximately 300 mGals and Hellas Basin approximately 150 mGals. This proposed basin, therefore, shows a gravitational anomaly signature of the right order of magnitude for a large Martian impact basin.

[29] The presence of a central negative anomaly offers the strongest argument against interpreting this proposed basin as an ancient impact; the other large Martian impacts do not have a central negative anomaly. The negative gravity anomaly and positive (thickened) crustal thickness anomaly are suggestive of a central peak, but impact basins of this size do not typically have central peak structures [*Wood and Head*, 1976].

[30] Where is the current topographic expression of this proposed ancient impact event? Repeated infilling and resurfacing can easily explain the lack of a basin structure, but what about the crater rim and ejecta blanket? The area of negative gravity anomaly and crustal thickening, where one would expect to find rim material [*Bratt et al.*, 1985; *Pilkington and Grieve*, 1992], does correspond with an arcuate ridge of highstanding, high-relief material. Mapped as HNu in the USGS map (Figure 2) [*Scott and Tanaka*, 1986], this arcuate topographic ridge is of the right age and in the right location to be remnant crater rim material.

[31] This basin rim and a tip of Acheron Fossae are the only Noachian-aged outcrops visible in the study area. The heavily cratered plains typical of the southern highlands, if present, have been mantled and buried by subsequent activity. *Frey et al.* [2001] have proposed that the entire northern lowland region is Noachian in age, based on the presence of numerous "quasi-circular depressions," visible in MOLA data, interpreted as craters. They have mapped no such hidden craters in Amazonis Planitia, indicating that they, too, would assign an Amazonian age to the surface. Indeed, the lack of craters in the *Frey et al.* [2001] study or in the *Head et al.* [2002] analysis of "stealth" craters underlying the Vastitas Borealis Formation, provides further evidence that Amazonis Planitia underwent a different history than that typical of the northern lowlands. In light of its unique history, it is somewhat ironic to note that Amazonis Planitia was originally seen as the type locale for young Martian surfaces, even giving the name to the Amazonian era.

3.3.2. Early Hesperian

[32] A large occurrence of Early Hesperian-aged ridged plains (Hr) is seen in the southwest region of the study area [*Scott and Tanaka*, 1986] (Figures 2, 4d, and 11b). The superposed wrinkle ridges are subdued in the central smooth unit, but appear again in the northeastern corner of the study area. In the southwest, the ridges are oriented approximately N5°E, and show a slight clockwise rotation across the region, culminating in an orientation of approximately N25°E in northeast Amazonis Planitia (see also discussion of *Plescia* [1993]). They appear to be circum-Tharsis in orientation, and are likely part of the system of circum-Tharsis wrinkle ridges found throughout the northern lowlands by *Head et al.* [2002, cf. Figure 7].

[33] Wrinkle ridges can be seen protruding through the central smooth unit, but there the relief between the ridge crest and the surrounding plain (typically 25–40 m, with one ridge rising 75 m above the plain) is approximately one third that of the less modified Hesperian ridges to the west and south (typically 80–150 m). This, together with stratigraphic relationships, suggests that the Hr unit underlies tens of meters of material (~40–125 m) that have mantled the basin floor since the emplacement of the ridged plains unit. Previous work showing that the ridges in the central smooth unit are significantly more subdued than ridges in the Vastitas Borealis Formation concluded that the ridged plains within Amazonis Planitia were mantled first by the Vastitas Borealis Formation and then by additional material [*Head et al.*, 2002].

3.3.3. Late Hesperian

[34] The Vastitas Borealis Formation (Hv) has been assigned a Late Hesperian age (Figure 3) [*Scott and Tanaka*, 1986], an age confirmed by a more recent study including "stealth" craters interpreted to be superposed on Hr (ridged plains) underlying the Vastitas Borealis Formation [*Head et al.*, 2002]. Contemporaneous units (Figure 3) include those of the numerous outflow channels, and several researchers have proposed that the northern lowlands were once the location of an ocean that formed as a result of the floods that formed the outflow channels [*Parker et al.*, 1989, 1993]. The outer contact of the Vastitas Borealis Formation in many areas corresponds approximately to the position of Contact 2, a boundary interpreted by *Parker et al.* [1989, 1993] to represent the shoreline of an ocean. *Head et al.* [1999] found that the average elevation of Contact 2 was approximately −3760 m. On the basis of an analysis of the stratigraphy and structure of the northern lowlands, *Head et al.* [2002] concluded that the Vastitas Borealis Formation averaged about 100 meters in thickness and represented the sedimentary residue of the emplacement and evaporation/sublimation of the outflow channel effluent emplaced in the northern lowlands [see also *Kreslavsky and Head*, 2001, 2002]. If Contact 2 of *Parker et al.* [1993] does indeed represent the shoreline of an ancient ocean, this would correspond to a depth in Amazonis Planitia of approximately 200 m (Figure 5e), for a total water volume of approximately 2×10^5 km^3. In any case, it is probable that a layer of the Vastitas Borealis Formation, perhaps of the order of 50–100 m thick, overlies the Hesperian ridged

plains (Hr) and underlies units presently exposed at the surface in Amazonis Planitia.

[35] At the northern boundary of the Amazonis Planitia central smooth unit, a volcanic unit extends WNW, with at least three visible flow lobes (Figure 4d). The easternmost visible flow emerges from beneath the aureole approximately 800 km from the summit of the Olympus Mons edifice. The 1800-km long flow unit is generally Tharsis-radial, but the eastern-most flows are clearly radial to Olympus Mons, suggesting that this material originated from a source in the Olympus Mons region, perhaps early Olympus Mons volcanism that was deflected to the west by the regional slope from Alba Patera (Figure 11c). It is also possible that lava was contributed from Alba Patera and/or the Tharsis Montes, which were volcanically active around this time (Figures 1 and 3), but the roughness signature visible in this unit [*Kreslavsky and Head*, 2000] is markedly different from that of the Alba Patera and Tharsis Montes Late Hesperian flows. The roughness map [*Kreslavsky and Head*, 2000] (Figure 4) shows that the visible Alba Patera and Tharsis Montes flow surfaces are rougher (at 2.4 km baselength roughness) than these flows. Furthermore, slope maps (e.g., Figures 5a and 5c) show that the presently visible Alba Patera lava apron has more dramatic internal relief than this flow. Due to the subsequent emplacement of the Olympus Mons aureole, the roughness signature of proto-Olympus flows cannot be known, but the lack of correlation with the signatures of early Alba Patera (Hal) and Tharsis (Ht_1 and Ht_2) flows, combined with the Olympus-radial orientation of the uppermost flows, leads us to conclude that the most likely provenance of this flow is pre-aureole Olympus Mons. If so, this unit confirms the prediction of *Morris and Tanaka* [1994] that there should be "lava flow fields beyond the aureoles" if the aureoles resulted from gravity spreading mechanisms or landsliding from a proto-Olympus Mons edifice.

[36] Also in the Late Hesperian (Figure 3), in the southern part of the region, channel outflow activity carved the Mangala Valles [*Tanaka and Chapman*, 1990; *Milton*, 1973]. Flow through Mangala Valles and Labou Vallis, the northwest branch of the Mangala Valles system, moved from south to north; the water debouching from the northern reach of the channel likely flowed down the topographic slope into the Amazonis basin (Figure 11c). The Amazonian-aged Medusae Fossae Formation (Figure 1) [*Scott and Tanaka*, 1986], which currently stands between Mangala and Amazonis, was not present at this time to be an obstacle to this Hesperian channel flow. Additionally, recent work by *Bradley et al.* [2002] shows that outflow channels from Labou Vallis can be traced approximately 300 km farther to the north, beneath the Medusae Fossae Formation. These channels must have carried a considerable volume of water and sediment into Amazonis Planitia. Quantifying the volume of material that flowed into Amazonis Planitia is difficult because both the discharge rate and the duration of flow must be known. Both *Baker* [1982] and *Komar* [1979] estimated that the Mangala Valles flood discharge was approximately 2×10^7 m^3/s. That figure was calculated using topography estimates from Viking, which gave an approximate channel depth of 100 m. MOLA data show that the average channel depth is closer to 250–300 m; a preliminary reexamination of their calculations with MOLA data suggests that if the channel was filled, the flood discharge would be closer to 1×10^8 m^3/s, an order of magnitude larger than the Viking-based value. It is interesting to note that, in the absence of a northern ocean, Mangala Valles outflow alone could fill the Amazonis basin to the height of the proto-Olympus lava flow, depending on the duration of the channel activity. If the discharge was at the level calculated from Viking, it would take approximately two months of outflow; if at the level estimated from MOLA data, it would take 8–10 days of channel activity. *Zimbelman et al.* [1992], arguing from Darcy's Law and probable hydraulic conductivities, generated dramatically lower flow rate estimates for the Mangala Valles outflow; at their estimated maximum flow rate of 10^5 m^3/s, filling the Amazonis basin would take approximately 30 years.

[37] Given the poor constraints on the relative timing of these three Late Hesperian events, six scenarios are possible. For clarity of discussion, each event is assigned a letter: the formation of the Mangala Valles (M), the pre-aureole Olympus Mons flow (O), and the emplacement of the Vastitas Borealis Formation (V). The possible orders of events, therefore, are the following: MOV, MVO, VMO, VOM, OVM, OMV. Each scenario will be presented below, then tested with MGS data.

[38] MOV (Mangala Valles outflow, proto-Olympus volcanism, Vastitas Borealis Formation emplacement): Water and sediment from Mangala Valles debouch into Amazonis Planitia. The water runs downslope toward the northern lowlands, ultimately ponding, infiltrating, freezing, boiling, and/or sublimating [e.g., *Kreslavsky and Head*, 2001, 2002]. Lava from Olympus flows westward. The proposed northern ocean, spreading southwards, is temporarily dammed by the flow and the rim of the ancient crater, but ultimately overtops them and floods the Amazonis Basin with approximately 2×10^5 km^3 of water. The ocean freezes and sublimates, leaving Vastitas Borealis Formation material draped over Amazonis Planitia, the proto-Olympus flow, and the northern lowlands.

[39] MVO (Mangala Valles outflow, Vastitas Borealis Formation emplacement, proto-Olympus volcanism): Again, water and sediment from the southern highlands flow into Amazonis Planitia. It is either frozen, lost to the atmosphere, or, if it remains liquid, continues north (down gradient) via infiltration and groundwater recharge or overland flow. The water feeds the nascent northern ocean that has begun to spread outwards from enclosed basins in the north. Ultimately, the waters rise high enough to fill Amazonis Planitia to approximately 200 meters depth (see Figure 5e). Liquid water not being stable at the surface, the ocean freezes solid and rapidly sublimates [e.g., *Kreslavsky and Head*, 2001, 2002]. If the proto-Olympus flow entered a liquid water ocean, we might expect to find pillow textures from cooling and quenching, and possibly basaltic glass fragments from phreatomagmatic explosions. If the lava flowed under a layer of ice, we might expect to see flat-topped domes [*Chapman et al.*, 2000; *Ghatan and Head*, 2001]; if it flowed across an icy surface, rootless cones ("pseudocraters") could form within the flow margins. If the eruption postdated the sublimation of the ice, the lava would have simply flowed out over a layer of dry Vastitas Borealis Formation material, and we would not expect to see evidence of phreatomagmatic interactions.

[40] VMO and VOM (Vastitas Borealis Formation emplacement, Mangala Valles outflow, proto-Olympus volcanism; Vastitas Borealis Formation emplacement, proto-Olympus volcanism, Mangala Valles outflow): In both scenarios, Mangala Vallis debouches into an ocean that filled the Amazonis Basin; we would not expect to see deltaic deposits because the slope is so shallow that the water entered essentially as sheet flow [see *Ivanov and Head*, 2001]. The proto-Olympus flow would behave as described under MVO. One difference between these two scenarios (VMO and VOM) is the fate of the sediment entrained in the Mangala Valles effluent: if the Mangala Valles outflow event predated the proto-Olympus lava flow, the sediment would have washed into the northern lowland. If not, we would expect to see evidence of a sediment trap.

[41] OVM (proto-Olympus volcanism, Vastitas Borealis Formation emplacement, Mangala Valles outflow): Lava from the proto-Olympus eruption flows westward across Amazonis Planitia. Together, the crater rim remnants and the flow create a barrier approximately 100 m high, temporarily preventing the rising northern ocean from entering Amazonis Planitia. This dam is ultimately overtopped, and water floods the basin. When the Mangala Valles outflow enters the basin, it simply deepens the water level and deposits its sediment load. If the Mangala Valles outflow event postdated the sublimation of the northern ocean, we would expect to find Mangala Valles sediments above the Vastitas Borealis Formation (Hv), and perhaps evidence of channels carved through the Hv deposits.

[42] OMV (proto-Olympus volcanism, Mangala Valles outflow, Vastitas Borealis Formation emplacement): As described under OVM, the proto-Olympus lava flow creates a dam, enclosing the Amazonis Basin. Water and sediments from Mangala Valles debouch into Amazonis Planitia. The water either infiltrates, sublimates, or creates a shallow lake (Figure 11c). If a northern ocean overtops the proto-Olympus lava flow, then the water would flow into the Amazonis Basin. Depending on the fate of the water from Mangala Valles, it either deepened the standing water, flowed across the saturated surface, or pooled above the ice. This last option seems unlikely, because if the climate in Amazonis Planitia could not support liquid water at the surface [*Mellon and Jakosky*, 1995], it seems very unlikely that a northern ocean would be liquid.

[43] Reexamining the data with these predictions in mind, some of the scenarios stand out as more plausible than others. MOC images (e.g., Figure 9c) of the proto-Olympus flow reveal rootless cones, as well as crater-like collapse structures that could result from the melting or sublimation of blocks of ice underneath the lava, implying that the lava did not flow across a desiccated surface. This suggests that the latter two scenarios, in which the proto-Olympus flow predated either of the aqueous events, are less likely. The groundwater or ground ice which mixed with lava to form the rootless cones could have been provided by the Mangala Valles outflow event, but that seems unlikely, due to the distance—more than two thousand kilometers—between the lava flow, at $\sim$40°N, and the northernmost trace of the channel, which *Bradley et al.* [2002] have placed at $\sim$10°N. The water or ice that fed the phreatomagmatic eruptions, therefore, most likely came from the northern ocean or its residual deposits. If correct, this narrows the six scenarios down to the three in which the northern ocean precedes the lava flow: MVO, VOM, and VMO.

[44] In summary, although subsequent events have produced deposits which have obscured the earlier history of Amazonis Planitia (Figure 4d), it appears likely that the proto-Olympus Mons flows post-dated the emplacement of the Vastitas Borealis Formation.

3.3.4. Early Amazonian

[45] At the beginning of the Amazonian, the Amazonis Basin is encircled by Lucus Planum and Hesperian-aged flows from Tharsis to the south, the Elysium rise and the heavily degraded remnants of the ancient impact basin to the west, the proto-Olympus Mons edifice to the east and the distal Olympus Mons flows to the north (Figure 11c). Subsequent to this, a series of collapse events along the flanks of Olympus Mons form a 550 km diameter aureole adjacent to the edifice on its west, modifying the western apron of pre-existing Olympus volcanic flank deposits (Figure 11d). At least two units (Aoa_1 and Aoa_4), representing discrete collapse events, are visible in the mapped area of the aureole. Other intermediate-aged aureole structures are found elsewhere around the edifice [e.g., *Scott and Tanaka*, 1986; *Morris and Tanaka*, 1994].

[46] The reason for the formation of the aureole structures at this time may have been the growth of the edifice to such a significant size that its flanks became unstable due to loading and flexure [e.g., *Comer et al.*, 1985; *McGovern and Solomon*, 1993]. Preferential formation toward Amazonis Planitia is likely to have been due to the regional slopes away from the Tharsis region toward Amazonis (Figure 1). Such regional slopes would enhance instabilities and large-scale gravity sliding. A further factor may have been the former presence of water or water-saturated sediments in Amazonis Planitia (e.g., Mangala Valles outflow, Vastitas Borealis Formation), a factor that would not have been as influential higher on the Tharsis slopes. Discussing gravity spreading models for the emplacement of the Olympus Mons aureole, *Tanaka* [1985] showed that ice in the Amazonis Planitia region could have lubricated the extensional motion, but he lacked a source for the ice. He proposed that hydrothermal circulation of water by Olympus Mons volcanism could have produced such ground ice, but the aqueous emplacement of water- or ice-rich sediments is a much simpler mechanism for bringing ice to the flanks of the proto-Olympus Mons edifice. The presence of a 50 m thick layer at the base of the aureole would lubricate surface extension and allow for an aureole growth rate of 3 cm/yr [*Tanaka*, 1985]. *Bulmer and McGovern* [1999] proposed that the aureole was emplaced as a gigantic landslide with total emplacement duration of less than an hour. Such a landslide would have generated a large quantity of dust that might easily have blanketed Amazonis Planitia and adjacent parts of the northern lowlands.

[47] In the detrended MOLA data (Figure 5d), the southwestern edge of the aureole scarp shows what appear to be fluid-like lobate flows (mapped in Figures 4d and 11d). A MOC image taken from near the western boundary of this material (Figure 9d) shows clear evidence of fluvial channel formation in an east-west direction, possibly representing dewatering flows from the exposure of ground ice by the emplacement process. These flows are clearly not volcanic; they show none of the surface textures of the Marte Valles

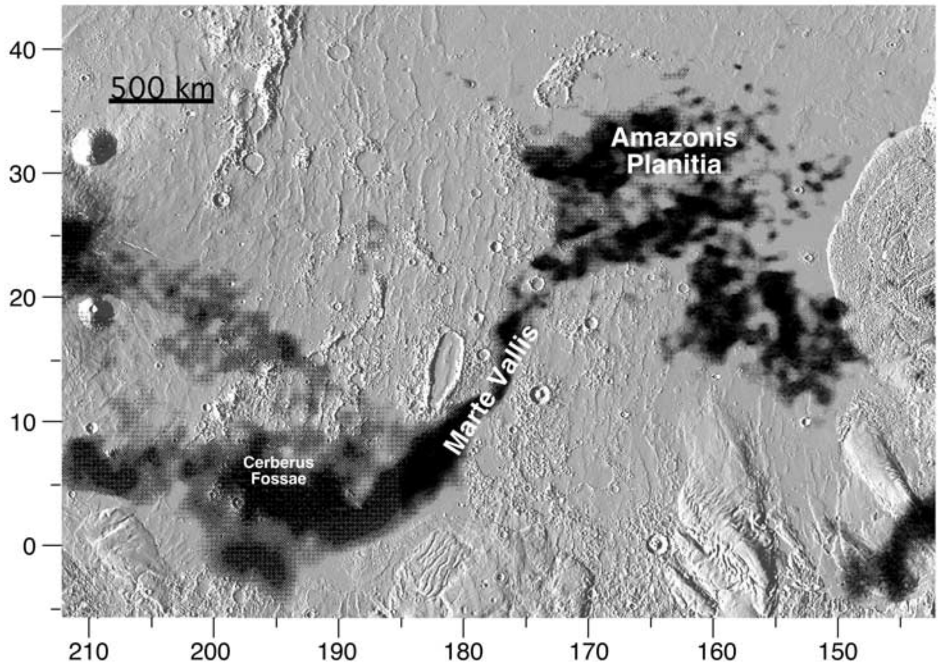


Figure 8. Radar data from 12 cm-wavelength telescope at Arecibo superposed over MOLA-derived gradient map for the Elysium and Amazonis Planitiae region (142°–212°W, −4°–42°N). Dark areas correspond to strong radar backscatter ($\sigma_{sc} > 0.25$) and correlate closely with regions of young volcanism. Lavas emerged from the Cerberus Fossae in northwestern Elysium Planitia [*Plescia*, 1990; *Keszthelyi et al.*, 2000] and flowed through Marte Valles into Amazonis Planitia. The post-aureole flows in southeastern Amazonis Planitia are also visible.

flood lavas, and they are much smaller in scale. Also, the sketch map in Figure 9d illustrates that the dewatering flows cut through a field of intercutting lava flow fronts before widening laterally and becoming difficult to trace. The morphology is similar to an Australian flood-out, where concentrated runoff from extreme rainfall events carves deep channels before broadening into sheet flow [*Bourke and Zimbelman*, 2001].

[48] Subsequent to the formation of the Olympus Mons aureole in the mapped area, flows from the southern Tharsis region flowed onto the southeastern portion of Amazonis Planitia (Figure 11e). It is difficult to trace the lava flows back to their origin, as their original paths are partially buried under impact ejecta and the Medusae Fossae Formation; the general direction of flow suggests that the lava originated at Arsia Mons and/or Pavonis Mons (Figure 1). The flows clearly curve around the Olympus Mons aureole, showing that this flow postdated the emplacement of at least the oldest unit of the aureole. These flows can also be seen in radar-based maps of *Harmon et al.* [1999, Figure 4d, Figure 8], who found that areas with significant surface roughness on decimeter scale lengths (which appear black in Figure 8) correlate strongly with areas of relatively young volcanism [*Harmon et al.*, 1992, 1999]. *Harmon et al.* [1999] have mapped these flows as originating in AHt_3, part of the Tharsis Montes volcanism. That seems logical on the basis of geographic proximity, but the stratigraphic correlation chart of *Scott and Tanaka* [1986] (Figure 3) shows that, as this volcanism post-dated the emplacement of the aureole, it must also have post-dated the AHt_3 volcanism, and instead correlates with At_4 or At_5. $At_{4,5}$ crop out much farther to the east, suggesting that this unit represents a discrete but contemporaneous flank flow event from Tharsis.

[49] Also prominent in the radar data of Figure 8 is a large radar-bright area to the west, interpreted as lava originating from eruptions in Elysium that flowed through Marte Valles into Amazonis Planitia. This material produces one of the four "brightest" radar signatures on Mars [*Harmon et al.*, 1999]. These radar-visible flows follow approximately the same course through Marte Valles as much younger flows [*Keszthelyi et al.*, 2000] (Figure 11i) but extend much further out into Amazonis Planitia (Figure 4b; Figures 8 and 11g). The fact that these are discrete flows is clear from MOC images, which show that the flows visible in radar data are much more heavily mantled than the uppermost flows of Marte Valles (e.g., Figures 9e and 9f).

[50] The radar data [*Harmon et al.*, 1992, 1999] were collected with a 12.6 cm wavelength radar, which translates into ground-penetrating depth of approximately a meter. Precise values for radar penetration depth vary as a function of surface moisture; due to the extreme aridity of the current climate, the ground penetration may be as deep as several meters [*Elachi*, 1987, pp. 238–239]. The flows are not visible in MOLA topography, and some MOC images taken in the radar-bright region are similar to those taken further east in areas that do not show radar backscatter; their lack of surface expression suggests that these flows have been mantled by overlying material. Figures 9e and 9f, showing a MOC image from the radar-bright region with an image

from the younger, overlying Marte Valles volcanism, support this hypothesis. Both surfaces show pressure ridges typical of rafted flows [*Keszthelyi et al.*, 2000], but the older flow surface (Figure 9f) rarely shows low-lying areas between rafted plates, clearly visible in the younger flow (Figure 9e). The fact that the topographically higher features are visible, while the low-lying features often are not, strongly supports the idea that aqueous and/or aeolian processes have mantled the lava surfaces. Comparison of the topography of the fresh flows and these deposits suggests that the thickness of the mantling material is on the order of a few meters to several tens of meters. Though evidence for the initial carving of Marte Valles (Figure 11f) has been buried by subsequent fluvial and volcanic activity, the presence of the debris-mantled, radar visible flows is indirect evidence that the channel must have been carved prior to the Mid-Amazonian eruption. *Scott and Chapman* [1995] have shown that Marte Valles cuts Amazonian material, constraining the initial outflow to the Early-Mid Amazonian.

3.3.5. Middle Amazonian

[51] During the middle Amazonian, Olympus Mons aureole formation continued, as did volcanic activity forming members of the Tharsis Montes Formation (Figure 3). During this time, the initial members of the Medusae Fossae Formation were emplaced. This unit spans much of the Amazonian Period (Figure 3) and consists of unconformable accumulations of easily eroded material; early deposits are draped over underlying topography and evidence of stripping (e.g., yardangs) indicates that deposition has ceased and erosion has been going on for undetermined periods of time. Outliers suggest that the deposit covered a much broader region in the past.

[52] *Sakimoto et al.* [1999] have recently reexamined the Medusae Fossae Formation on the basis of MOLA data and have found that the upper, lower, and middle member designations made from Viking images often conflict with the stratigraphy apparent in MOLA data; for example, in several places Aml, the lower member, is above Amu, the upper member. The MFF is lightly cratered (<200 craters >2 km $\times$ 10^6 km^2) and interpreted to be Amazonian in age, with the lower boundary shown to be well into the Amazonian Period [*Scott and Tanaka*, 1986; *Greeley and Guest*, 1987] (Figure 3). Numerous hypotheses have been proposed to account for the origin of these deposits (see summary by *Zimbelman et al.* [1999]) and studies are underway to assess the full range of these hypotheses using new MGS data [*Zimbelman et al.*, 1997, 1999; *Sakimoto et al.*, 1999; *Head*, 2001]. As reviewed and summarized by *Zimbelman et al.* [1999], proposed hypotheses for the origin of the MFF include paleopolar deposits related to true polar wander, ignimbrites, aeolian deposits, and ocean-related deposits. Recently, *Head* [2001] has drawn attention to the similarity of the MFF to polar and circumpolar deposits seen in MGS data and assessed origins related to 1) equatorial volatile deposition during obliquity extremes, and 2) orographic deposition during late-stage fluvial channel events [see also *Head and Kreslavsky*, 2001b, 2001c].

3.3.6. Late Amazonian

[53] Superposed on the mid-Amazonian radar-visible lava flows are young lava flows that correspond to the topographically lowest sections of MOLA profiles. The presence of these low-lying lava flows suggests that a fluvial event, stratigraphically between the eruptions, carved channels through the older flows; the young flows are preferentially flowing through these channels, resulting in the presently visible inverted topography (Figures 9g–9i). On the basis of previous analyses, it is known that sediment-laden water flowed northeast from Elysium Planitia, through Marte Valles into Amazonis Planitia [*Scott and Chapman*, 1991, 1995; *Plescia*, 1990] (Figure 11h). Due to the previously formed topographic barriers at the margins of the basin, the effluent almost certainly ponded in Amazonis Planitia, depositing sediments that softened the flow surface textures; the water then most likely infiltrated, froze and sublimated. In the detrended MOLA data, channel-like features can be seen to cut through the plain (see Figure 5d, fine-scaled features in Figure 11h); these may represent flow across a dry surface, but are suggestive, in their profile and discontinuity, of channels carved within a standing body of water by subaqueous current flow (see discussion of hyperpycnal flow by *Ivanov and Head* [2001]).

[54] The rough correlation of some of these channels with the mid-Amazonian lava flows (see Figures 8 and 11g) could suggest that they are lava flow tubes, but the preponderance of the evidence supports an aqueous interpretation. In particular, the cross-sectional morphology of the channels near the lava (Figure 12, profiles A, C) is virtually identical to that of channels in northeastern Amazonis that are tens of kilometers away from the flow (Figure 12, profiles B, D, E). The cross-sectional profiles of the Amazonis Planitia channels (Figure 12, profiles A–E) are marked by a broad, flat bottom, often cut by a deeper central channel. By contrast, the dendritic channels at the head of Marte Valles, in western Elysium [*Head and Kreslavsky*, 2001a], are much narrower and have steeper sides (Figure 12, profile F). The volcanically resurfaced channels within Marte Valles (Figure 12, profile G) are much deeper and have much steeper sides than the channels on the floor of the Amazonis basin. The change in profile from the narrowly carved channels within the valley to the broader form within the basin is also consistent with catastrophic flow onto a desiccated plain, as in Australian flood-outs [*Bourke and Zimbelman*, 2001].

3.3.7. Latest Amazonian

[55] Volcanic material from Elysium Planitia (the Cerberus Formation of *Plescia* [1990]) flowed through Marte Valles, occupying and resurfacing the previously-carved channels, ultimately extending out into the western edge of Amazonis Planitia (Figure 11i). At the southwest edge of Amazonis Planitia, a flow front can be seen to be superposed on an intrabasinal channel (Figure 4d), supporting the previously suggested hypothesis that this most recent volcanism postdated Marte Valles fluvial activity [*Plescia*, 1990; *Keszthelyi et al.*, 2000]. The slope through Marte Valles is currently less than $0.1°$; *Gregg and Sakimoto* [2000] have shown that this implies a high lava effusion rate, on the order of 10^3 to 10^4 m^3/s.

[56] Crater counts on lava flow surfaces within Marte Valles by *Hartmann et al.* [1999] and *Berman et al.* [2001] have been interpreted to indicate absolute ages ranging from one to twelve million years, but all within the latest 1% of Martian history; this young age is supported by the virtually pristine flow surface textures visible in MOC images (see

discussion by *Keszthelyi et al.* [2000]). The crater dates are accurate to approximately a factor of two, depending on the *R* value used (see discussion by *Hartmann and Neukum* [2001]), but show that this young volcanism is certainly younger than ~24 My—that is, well within the youngest 1% of Martian history—and probably much younger.

[57] The unusually smooth MOLA track (Pass 31) that drew early attention to this region actually stretched beyond Amazonis Planitia and through the Vastitas Borealis Formation; close examination shows that the smoothest section within it is the portion running across the central smooth unit of Amazonis Planitia (Figure 7). *Kreslavsky and Head* [1999] showed that the Vastitas Borealis Formation has a characteristic 2.4 km wavelength roughness, which *Head et al.* [2002] interpreted to be sedimentary residue that comprises the Vastitas Borealis Formation. The central smooth unit of Amazonis Planitia is completely smooth at kilometer scales, lacking this 2.4 km roughness signature, because it has been resurfaced several times since the late Hesperian, and the exposed Vastitas Borealis Formation has not.

4. Discussion

4.1. Flow Thickness of the Youngest Marte Valles Flows

[58] MOLA data show that the youngest Marte Valles flows have distal thicknesses of 20–40 m, which differs from estimates made in the channels closer to the flow origins. This difference may be due to distal thickening of the flow terminus related to cooling-limited inflation effects or to supply-limited drainage of the more proximal reaches of the lava channel [e.g., *Pinkerton and Wilson*, 1994]. The thickness of the flows within Marte Valles is less than the distal thickness, but more difficult to measure. On the basis of Viking images, *Plescia* [1990] estimated flow thicknesses of ~10 meters. *Keszthelyi et al.* [2000], using MOC images, concurred, but modeled flows of varying thicknesses. *Therkelsen et al.* [2001], using MOLA data, found that the lava surface within Marte Valles was only a decimeter-scale "veneer" over the channel floor. In this study, we found that individual rafted plates stand approximately 2 m above the intraplate material, but that measuring the entire thickness of a flow is very difficult because of the propensity of the lava for exploiting previously carved channels (e.g., as in Figures 9g and 9i). Often, MOLA profiles show that instead of standing above the surrounding terrain, a lava channel will show the lowest elevations of the profiles, indicating that the lava flowed through a pre-existing fluvial channel. Figure 9i shows a section from a MOC image where a young flow crosscuts an older flow (for context, see Figure 9g). The MOLA profile (Figure 9h) illustrates that the youngest material is the lowest-lying, suggesting that it is utilizing a channel carved through the older flow by a fluvial episode that occurred between the volcanic events. The actual thickness of the lava flow, therefore, is entirely dependent upon the original depth of the channel and how deeply the channel is filled with lava today, neither of which can be readily determined with present data.

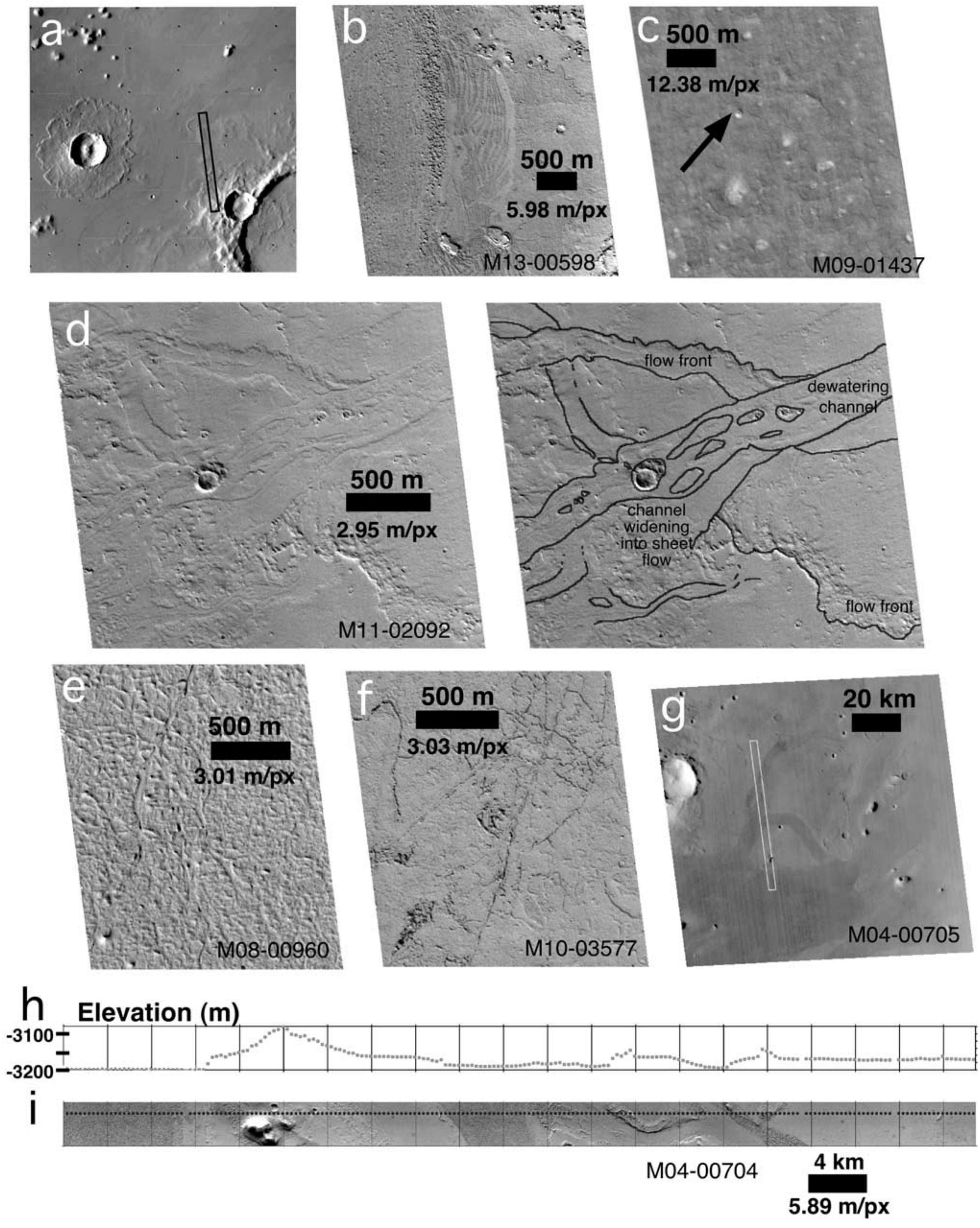
4.2. Volcanic-Fluvial Interactions in Marte Valles

[59] We find evidence for at least two discrete episodes of channel activity and lava infilling. First, Marte Valles was carved in the early-mid Amazonian [e.g., *Scott and Chapman*, 1995], then flooded by the radar-visible lavas that extended across Amazonis Planitia. Later, a second episode of fluvial outflow activity carved channels through those lava flows and mantled lava surfaces within Marte Valles and across Amazonis Planitia. This was followed by the youngest Marte Valles volcanism, which flowed into the western margin of Amazonis Planitia and created the virtually pristine lava flow surfaces visible in MOC images.

[60] The first, valley-carving channel activity (Figure 11f) likely resulted from Elysium Planitia overflow. *Burr et al.* [2000] and *Burr and McEwen* [2001], using Manning's equation modified for Martian gravity, calculated volumetric discharges and showed that the volume that would have filled Marte Valles is approximately equal to the volume of channels flowing into Elysium Basin from the north, suggesting that one large flooding event could have carved Marte Valles. *Head and Kreslavsky* [2001a] have mapped a dendritic channel system in eastern Elysium draining into Marte Valles. These observations suggest that the basin was flooded from the north and then the ponded water drained through Marte Valles, leaving the small dendritic channels documented by *Head and Kreslavsky* [2001a] (see typical profile in Figure 12, profile F).

[61] What is the temporal relationship between the second channel outflow event and the youngest volcanism in Marte Valles? *Berman et al.* [2001] used crater counts to determine that at least one flow occurred within one million years of channel-forming activity. The abundance of pseudocraters in the Marte Valles lava flows, interpreted by *Lanagan et al.* [2001a, 2001b] to be phreatomagmatic rootless cones, provides geologic support for a close temporal relationship. At these latitudes, under present climatic conditions, shallow subsurface ice is not stable [*Mellon and*

Figure 9. (opposite) Viking and Mars Orbiter Camera (MOC) images illustrating various aspects of Amazonis Planitia and Marte Valles. (a) and (b) A channel within Marte Valles interpreted on the basis of Viking data (a) to be a non-resurfaced fluvial channel [*Scott and Chapman*, 1991; *Plescia*, 1990] but which M13-00598 (b) reveals to have been volcanically resurfaced. Crater-topped cones similar to those *Lanagan et al.* [2001a, 2001b] interpreted to be phreatomagmatic rootless cones can be seen in the upper right corner. (c) M09-01437, from the surface of the proto-Olympus flow in northern Amazonis Planitia, unit (Hop) in Figure 4d. (d) M11-02092 and sketch map, from the fluid lobate material emerging from the Olympus Mons aureole: dewatering flows, possibly due to ground ice exposed by aureole emplacement. (e) M08-00960: typical Marte Valles lava surface showing pressure ridges and lava rafting; compare with (f). (f) M10-03577: surface textures from a radar-bright area (see Figure 8). The radar-visible lava flow is heavily mantled; pressure ridges are still visible, but low-lying areas between rafts have been filled in. (g) M04-00705, also from Marte Valles: context image for (i). (h) MOLA profile corresponding to (i): inverted topography of the lava channels. (i) M04-00704: a young, low-albedo flow crosscuts an older, higher-albedo flow.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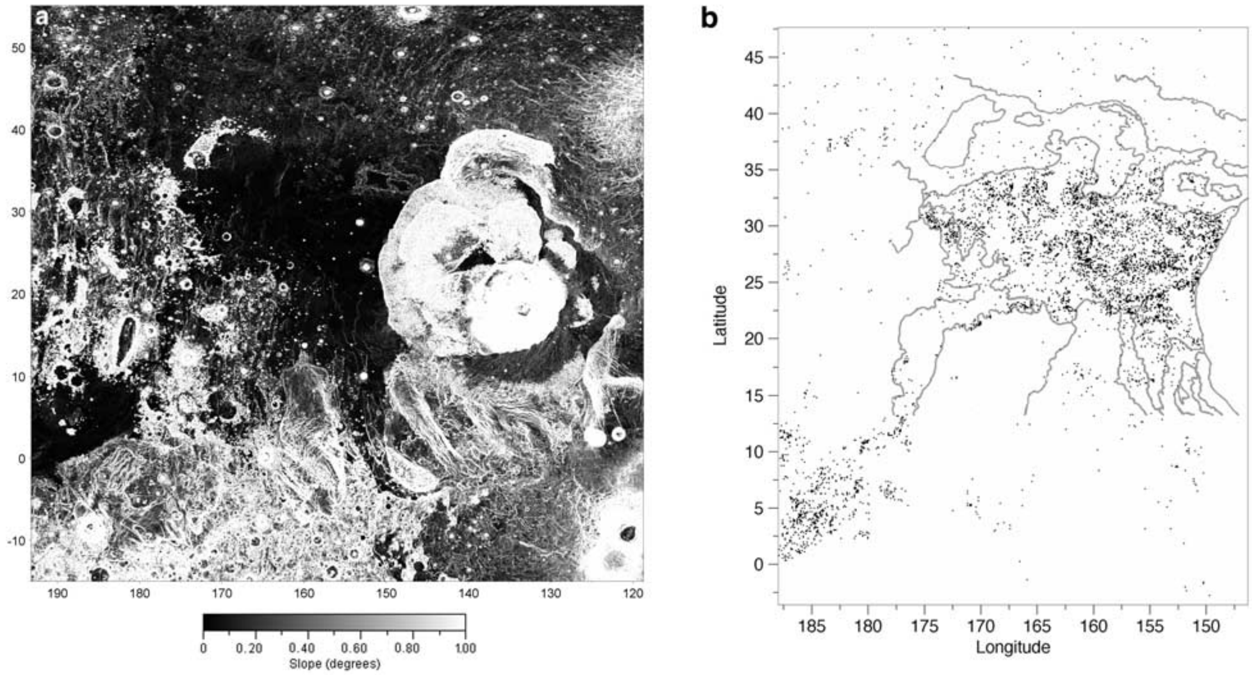

Figure 10. (a) Slope map for the Amazonis Planitia region. Note scale stretched such that any point with a slope greater than one degree is saturated white. (b) All points at which slope was <0.01°, with sketch map (see Figure 4d) overlain. Note the high density of points with near-zero slope within the central smooth unit of Amazonis Planitia.

Jakosky, 1993, 1995; *Mellon et al.*, 1997], suggesting that the lava would have had to follow the channel outflow within approximately 10^5 years.

[62] On the basis of these observations, then, it is likely that fluvial channel activity and volcanism were closely related in time. A model to account for this observation involves a genetic relationship between the fluvial and volcanic events (Figure 13), as originally outlined by *Plescia* [1990], and in a manner similar to that proposed in other regions by other workers [e.g., *Carr*, 1996, pp. 58–60; *Russell and Head*, 2001a, 2001b] (see summary by *Head and Wilson* [2002]).

[63] Many of the lavas that are observed in Elysium Planitia have been traced back to fissures in the Cerberus region [*Plescia*, 1990], fractures radial to the Elysium magmatic rise. Fractures and structures radial to magmatic complexes are often the sites of surface deformation related to the emplacement of magma-filled cracks, or dikes in the subsurface [e.g., *Parfitt and Head*, 1993; *Head and Wilson*, 1993; *Ernst et al.*, 1995; *Wilson and Head*, 2002]. In addition, in the Amazonian, Mars was very likely characterized by a thick global cryosphere, which was essentially a global aquitard to the groundwater system below [e.g., *Clifford*, 1993] (see summary by *Head and Wilson* [2002]). Often the global aquitard (the cryosphere) was sufficiently thick and continuous to build up hydrostatic pressure in the underlying groundwater system [e.g., *Carr*, 1987, 1996, pp. 58–60].

[64] In the context of this setting, we envision that magma was propagated as a dike laterally and vertically from the Elysium rise, extending toward the surface and breaching the cryosphere, which had been serving as an aquitard to groundwater under pressure (Figure 13) [see also *Russell and Head*, 2001a, 2001b]. When the fracture immediately preceding the propagating dike ruptured the cryosphere, the water, under hydrostatic pressure, emerged at very high flow rates, and continued to flow until equilibrium pressure was reached. The groundwater released by this catastrophic outflow flooded the Elysium Basin and drained through Marte Valles at the eastern end of the Elysium Basin, carving new channels in the valley, and ultimately debouching into Amazonis Planitia. The cracking of the cryosphere was shortly followed by the dike breaching the surface and erupting flood lavas. Lava from the ensuing eruption quickly flowed across the surface and followed the channel structures through Marte Valles and down into Amazonis Planitia. Associated pyroclastic activity has been proposed to be a major source of fine-grained material forming the Medusae Fossae Formation [*Keszthelyi et al.*, 2000].

[65] The surface of the fluvially emplaced water likely boiled and then froze [e.g., *Carr*, 1996, pp. 68–69; *Kreslavsky and Head*, 2001, 2002]. At the water-lava interface, the water may have infiltrated the surface. The temperature, porosity and permeability of the surface determined whether and for how long the water ponded before infiltrating or freezing. Ponded water will freeze solid rapidly and sublimation will occur in on the order of 10^6 years [*Mellon and Jakosky*, 1993, 1995; *Mellon et al.*, 1997; *Kreslavsky and Head*, 2001, 2002]. As the ice eventually completely sublimated, it left behind a residual layer of previously entrained sediment. *Head* [2001] has outlined a scenario in which at least part of the Medusae Fossae Formation may be due to fluvial channel emplacement. In this scenario,

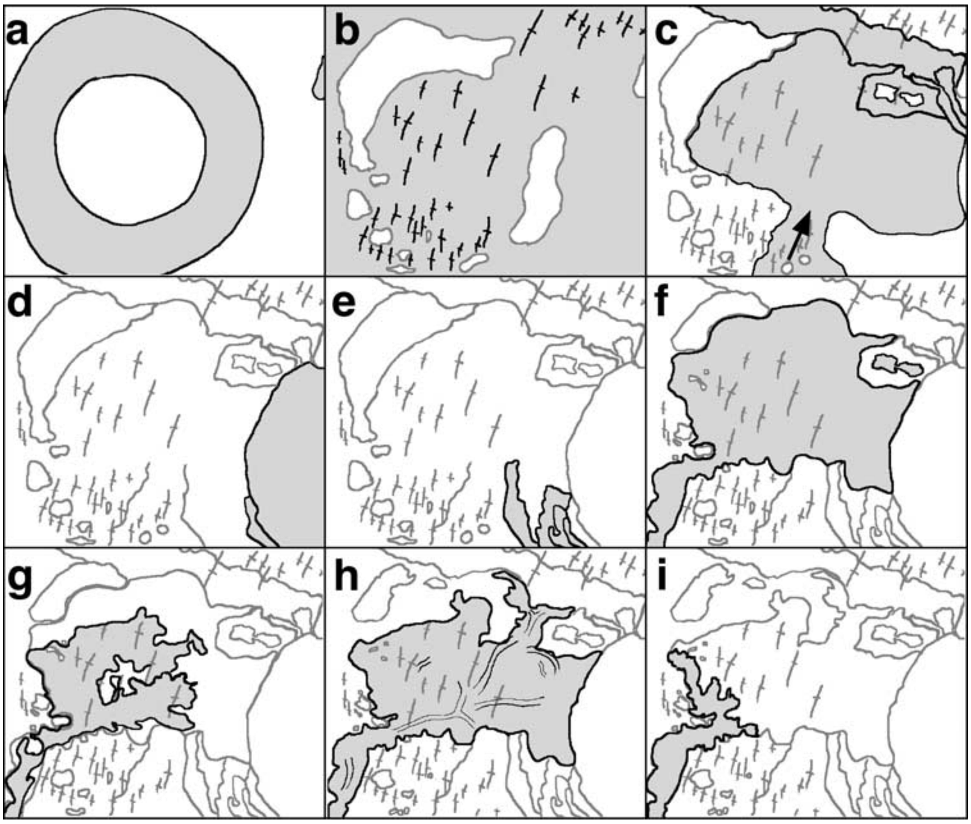

Figure 11. Paleogeographic sketch maps. Refer to Figure 4d for unit map. (a) Large impact event in the Noachian or earliest Hesperian. (b) Emplacement and tectonic deformation of the Hesperian ridged plains. (c) Lava flows from the pre-aureole Olympus Mons volcano form rectilinear depression and unit (Hop). Hesperian outflow events from Mangala Valles flow northward into Amazonis Planitia (see arrow), eroding and embaying the remaining crater rim. (d) Emplacement of the Olympus Mons aureole and dewatering flows. (e) Lava flows, probably originating in the Tharsis Montes, flow around the aureole. (f) Marte Valles carved, Amazonis Planitia flooded. (g) Lava flows from Elysium Planitia pirate the channels in Marte Valles and flow into Amazonis Planitia. (h) A propagating dike breaches the cryosphere in Elysium Planitia, catastrophically releasing water which resurfaces Amazonis Planitia and carves new channels into the Marte Valles lava flows. (i) The dike breaches the surface, flooding lavas into Elysium Planitia which flow through the re-carved channels into western Amazonis Planitia.

evaporation and sublimation of these fluvial channel effluents is followed by condensation of the volatiles and their redeposition at the orographic rise represented by the lowland-upland scarp. *Dohm et al.* [2000] have proposed that the Medusae Fossae Formation was shaped by large-volume fluvial activity originating on Tharsis and debouching into the Amazonis Planitia region during the Noachian or earliest Hesperian; effects of such activity would be similar to those seen from the Mangala Valles and Marte Valles outflow events discussed here.

4.3. Unusual Rectilinear Basins in Amazonis Planitia

[66] In northeastern Amazonis Planitia (Figures 2 and 4) are two rectilinear basins of enigmatic origin (Figure 14). They were mapped by earlier workers (Figure 2) as rimmed by Aa_1, the oldest member of the Amazonian-aged Arcadia Formation, and floored by Aa_3, an intermediate Amazonian-aged member of the Arcadia Formation (Figure 3) [*Scott and Tanaka*, 1986]. The floor of the western basin is approximately 100 m below the floor of Amazonis Planitia (the eastern basin is somewhat shallower, its floor being approximately 70 m lower than the surrounding plain) (Figures 4a and 14). Both basin floors are entirely smooth (Figure 4c) and similar to the rest of the floor of central Amazonis Planitia, suggesting that they may have enclosed ponded water for some interval. A narrow spillway between the basins can be observed (Figure 14, see arrow), suggesting that one of the basins filled and then poured out into the other. Examination of the surface texture of the depression margins in MOC images and in roughness maps (Figure 4c), as well as in the detailed topography (Figure 14) strongly suggest that the basins are entirely enclosed by high-relief material that is lobate and rugged, and appears to be volcanic in origin.

[67] This high-relief material is interpreted to be early proto-Olympus Mons flows of Late Hesperian age that extended out into the Amazonis basin prior to the formation of the aureole. We interpret the rectilinear aspect to be due to the flows extending radially from the direction of Olympus Mons, and then encountering wrinkle ridges on the underlying Hesperian ridged plains (Hr) striking almost normal to the direction of the flow of lava. Though a

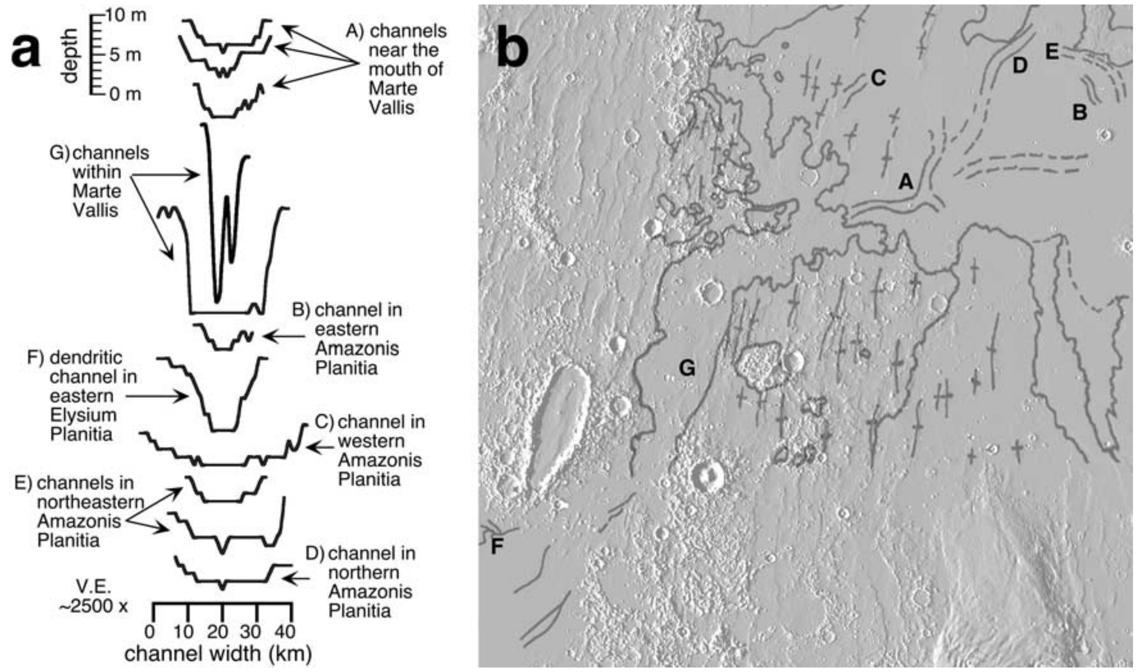

Figure 12. (a) Cross-sectional profiles of channels within the Amazonis Planitia region derived from MOLA 32 × 64 gridded data and (b) location map of profiles. A–E are from the floor of Amazonis Planitia and are interpreted to be hyperpycnal, or subaqueously incised channels (see discussion in text). They are marked by a broader, shallower cross-section than channels at the head of and within Marte Valles (F and G, respectively), due to the lack of lateral confinement.

wrinkle ridge is not presently visible there, the strike of the western margin of the basin corresponds closely to the strike of wrinkle ridges to the immediate north (Figure 5d). It seems plausible that the flows banked up against the wrinkle ridges, changed direction, and then extended laterally until meeting one of the other radial flows. In this manner, the wrinkle ridges served as barriers which caused the flows to form rectilinear basins. If this interpretation is correct, then the present depth of the basins (Figure 14) is a better approximation of the original elevation of the Hesperian ridged plains (or the overlying Vastitas Borealis Formation) than the present surface of the central smooth unit in Amazonis Planitia (Figure 4d). On average, the basin floors are 70–100 m below the surrounding plain (Figure 14), similar to the independently derived estimate of 40–125 m of mantling material deposited on top of the Hesperian ridged plains (Hr). Interestingly, the uppermost lava flows from pre-aureole Olympus Mons clearly tend to flow around this structure (Figure 4d), showing that it is the oldest of the pre-aurole flow units.

4.4. Effects of Regional Tectonism

[68] The structural history of the region also played a role in the shaping of the current Amazonis Planitia surface. Downwarping of the area surrounding the Tharsis Montes [*Phillips et al.*, 2001] could have allowed for increased basin fill in eastern Amazonis Planitia, and could therefore be responsible for the relatively greater thickness of the deposits close to Olympus Mons; in the eastern half of Amazonis Planitia, there are no visible wrinkle ridges, though ridges can be seen to the north and south. The complete burial of the wrinkle ridges suggests that the mantling layers are thicker there than they are further west, of the order of 100–200 meters (Figure 5d). Additionally, isostatic rebound or increased subsidence from the increased load on Tharsis or the emplacement of the Olympus Mons aureole could be responsible for the fractures that can be seen in southeastern Amazonis Planitia (Figure 5d).

4.5. Evidence for Water in Amazonis Planitia

[69] There is other evidence for water—either liquid or in ice form—in Amazonis Planitia. *Lanagan et al.* [2001a, 2001b] have argued that the rootless cones present in the Marte Valles lava flows are phreatomagmatic eruptions resulting from the presence of water ice in the subsurface. We have identified additional small domes interpreted to be rootless cones in Marte Valles, as well as in the proto-Olympus Mons flow. Indirect evidence for water in Amazonis Planitia includes the channels to the south and west of the basin. Marte Valles clearly debouches into Amazonis Planitia, and detrended MOLA data show channel-like depressions. There is less direct evidence that outflow from Mangala Valles reached Amazonis Planitia, but the channels did reach beyond the dichotomy boundary [*Bradley et al.*, 2002] and probably continued northward, carrying water and sediments into the Amazonis Basin.

[70] Could the apparent sedimentary deposits have resulted from aeolian deposition? MOC images and thermal inertia data show that aeolian activity has certainly altered the surface of Amazonis Planitia (Figure 9) throughout its recent history, but it is presently unknown whether the dunes and streaks typical of this region are 1) modifications of sedimentary deposits or 2) whether they represent a major influx of material by aeolian processes. Because of

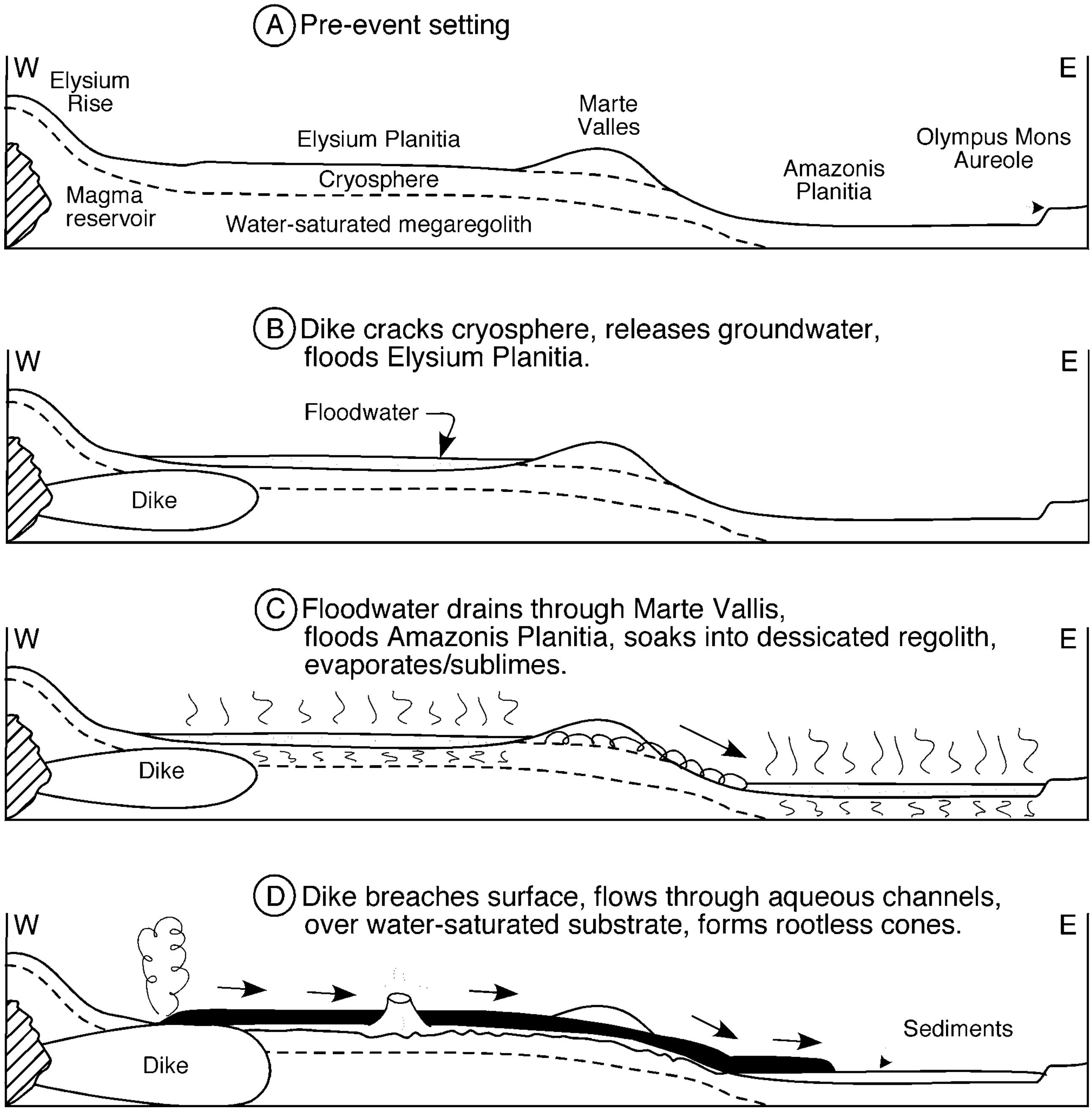

Figure 13. Diagrammatic and interpretative cross-section illustrating the relationship and history of dike emplacement, cracking of the cryospheric seal, release of confined groundwater, and the eruption of lava in the Elysium-Amazonis region. (a) Pre-event setting in a profile from the Elysium Rise, across Elysium Planitia and through Marte Valles (dome represents the high topography through which the channel, upper dashed line, passes), and into Amazonis Planitia. (b) Dike propagates laterally from below the Elysium rise and penetrates the cryosphere. (c) Release of groundwater under hydrostatic pressure. (d) Further propagation of the dike penetrates to the surface, causing an eruption. Lavas follow floodwaters down toward Amazonis Planitia, interacting with the recently emplaced water and sediment deposits. From Head and Wilson (manuscript in preparation, 2002).

the evidence for fluvial emplacement of sediments in Amazonis Planitia, we presently favor the first option.

5. Summary

[71] MGS data provide a view of the surface of Mars with unprecedented clarity, and also allow a more detailed look into the interior than ever before. Gravitational anomalies [*Smith et al.*, 1999a] reveal a ring-shaped pattern similar to that seen at other major Martian impacts. The correlation between the predicted area of crustal thickening [*Zuber et al.*, 2000] with an arcuate topographic ridge of high-relief, highly modified terrain, is strongly suggestive of a Noachian- or Early Hesperian-aged major impact event (Figure 11a).

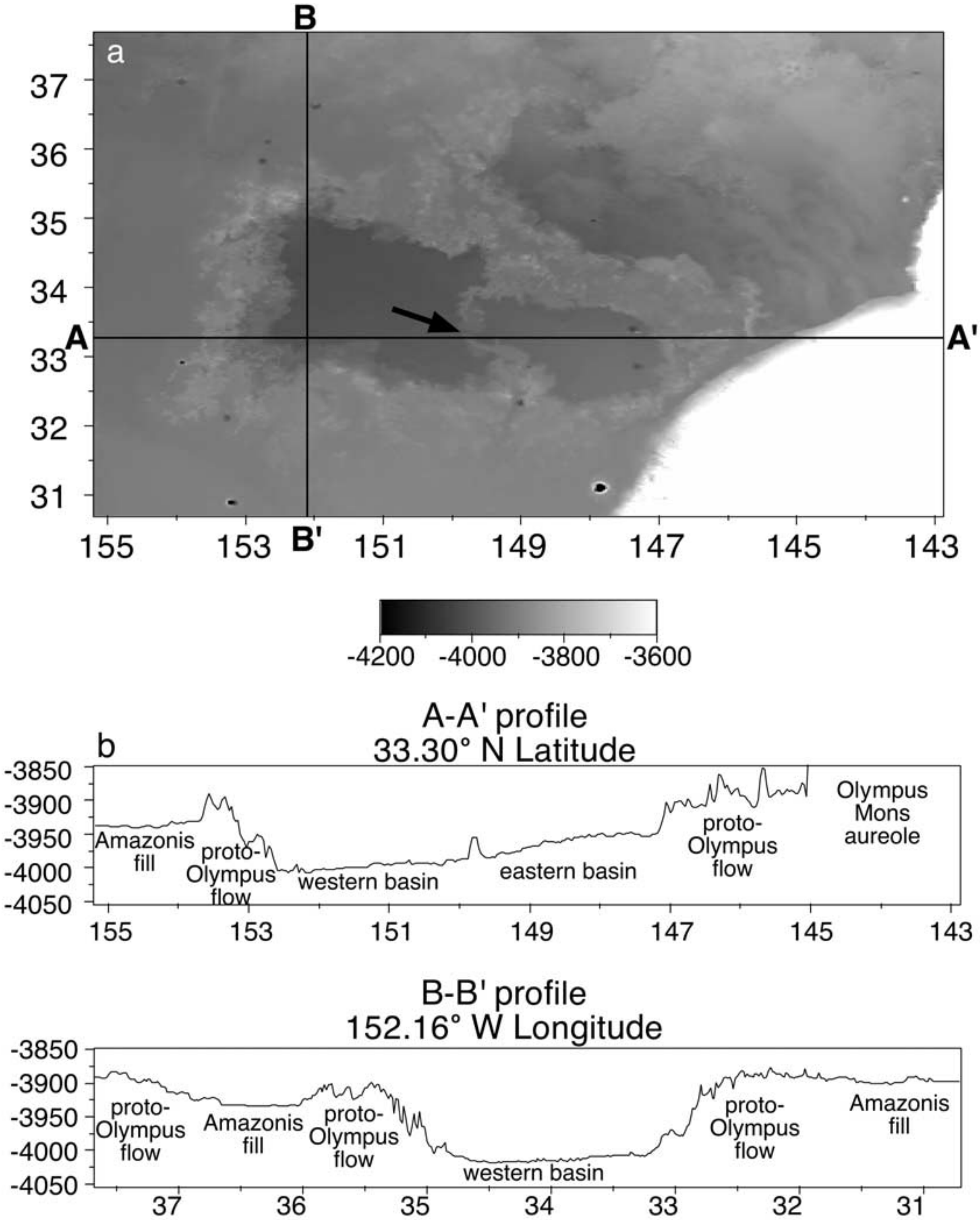

Figure 14. (a) Topographic map of the area of the rectilinear depressions, showing the lobate flow-like nature of the north and south margins, their orientation parallel to a direction radial to proto-Olympus Mons, and the similarity of their orientation to the extensive proto-Olympus flow just to the north. Also note that the margins trending in a direction just east of north are parallel to the orientation of wrinkle ridges in the underlying Hesperian ridged plains (Hr), well-illustrated in Figures 5b, 5c, and 5d and in Figure 4d. The nature and configuration of the rectilinear depression margins supports the interpretation that they represent proto-Olympus Mons volcanism that flowed into Amazonis Planitia and was deflected upon encountering wrinkle ridges in the underlying Hesperian ridged plains. (b) Topographic profiles across the rectilinear depressions, showing the flat floor of the interior, and its greater depth compared to Amazonis Planitia. This supports the interpretation that the floor was protected from much of the sedimentation and subsequent lava flows entering Amazonis Planitia by the marginal barriers, and thus its surface elevation represents a closer approximation of the original Hr or Hv elevation. Arrow in (a) shows possible location of spillover channels.

[72] MOLA also provides evidence that the Hesperian-aged ridged plains underlie the current Amazonis Planitia surface: wrinkle ridges, continuous in orientation with those in a circum-Tharsis ring that covers half of Mars [*Head et al.*, 2002], protrude through the overlying material. The emplacement of the wrinkle-ridged volcanic plains was the first resurfacing event for which we have data (Figure 11b); the repeated resurfacing of Amazonis Planitia, which has continued until very recently, led to the unusual smoothness of the central smooth unit of Amazonis Planitia (e.g., Figure 10).

[73] Reduced relief of the wrinkle ridges within the central smooth unit, when compared to those in unmodified Hr, shows that between 50 and 100 m of material is mantling the intrabasinal ridges, and as much as 150–200 m of material has completely buried the ridges in easternmost Amazonis Planitia. There are several sources for this material. Volcanic material from southern Tharsis flowed into the southeast corner of the region after the emplacement of the Olympus Mons aureole; the flows appear to reach 23°N, but one flow shows no clear distal margin (Figure 5d), suggesting that the flow may have continued for some distance into Amazonis Planitia. Perhaps more importantly, at least two volcanic phases produced flows into Amazonis Planitia from the west, from Elysium Planitia. Radar mapping [*Harmon et al.*, 1999] and Viking [*Plescia*, 1990] and MOC images [*Keszthelyi et al.*, 2000] reveal two distinct flow events debouching into Amazonis Planitia through Marte Valles (Figures 11g and 11i). Aqueous deposition also contributed material to Amazonis Planitia; the Mangala Valles, to the south, are a large system of channels that transported significant volumes of water and sediment from the southern highlands into the Amazonis region (Figure 11c). Another source of fluvial activity is from the west (Figures 11f and 11h); the fluvial origin of Marte Valles was first identified from Viking images [*Scott and Chapman*, 1991, 1995]. In addition, we interpret the structures within the proto-Olympus flow of apparent phreatomagmatic origin (Figure 9c) to mean that the flow unit was emplaced on top of the water-rich Vastitas Borealis Formation, which is correlated with the outflow channel effluents and may be related to the proposed northern ocean of *Parker et al.* [1989, 1993].

[74] Each resurfacing event smoothed the surface at different scales; the volcanic flows erased any prominent topographic features and filled in craters [cf. *Hartmann et al.*, 1999] and the aqueous events created laterally extensive sedimentary units that softened the rough-textured volcanic surfaces. The youngest of these, covering even early-mid Amazonian lava flows [*Harmon et al.*, 1992, 1999] occurred recently enough to remain almost entirely unaltered, creating the current surface, the smoothest plains on Mars.

[75] The extreme youth of the youngest volcanism and its associated fluvial activity suggest that Mars is volcanically active today; for reference, the Marte Valles flood volcanism is approximately contemporaneous with the emplacement of the Columbia River Basalt Group on Earth [*Hooper*, 1997; *Tolan et al.*, 1989]. It also suggests that liquid water was present, if not stable, on the Martian surface within the last 24 million years. The smoothness and youth of Amazonis Planitia, the two most distinctive features of the region, together point to a history of regional resurfacing that extends back more than three billion years, and has continued until the geologic present.

[76] The most important factors in producing the smoothest plains on Mars include 1) the formation of a barrier by the proto-Olympus Mons flow unit between outflow channel effluents from the south and the northern lowlands, 2) the trapping in the resulting basin of fluid lava flows and sedimentary effluent from the outflow channels, and 3) the very young volcanic and fluvial activity from Elysium Planitia.

[77] The dike swarm feeding the lava flows in Elysium Planitia is likely responsible for propagating the fracture that breached the damming cryosphere in southeastern Elysium Planitia and led to the catastrophic outflow of water through Marte Valles and into Amazonis Planitia (Figure 13) [*Head and Wilson*, 2002].

[78] The geological environment and history of Amazonis Planitia also has astrobiological implications. The most recent of the lava flows associated with the emplacement of these plains have been dated as extremely young geologically (less than 24 million years old [*Hartmann and Berman*, 2000]). If fossil or extant life existed at depth in the subsurface groundwater system at this time (a troglodytic fauna), it is highly likely that they would be among the material erupted to the surface during the cryosphere-cracking, dike-emplacement event (J. W. Head and L. Wilson, A model of simultaneous dike intrusion, cryospheric cracking, groundwater release and the eruption of lava: Examples from the Elysium Rise, Mars, manuscript in preparation, 2002), and washed down into Elysium and Amazonis Planitiae. The fate of such effluents under Mars conditions has recently been modeled [*Kreslavsky and Head*, 2001, 2002] and it has been shown that standing bodies of water at this scale would quickly freeze over and sublimate, leaving a sedimentary sublimation residue. Thus, Elysium and Amazonis Planitiae may be excellent locations to sample recently emplaced troglodytic faunal remains.

[79] **Acknowledgments.** We gratefully acknowledge the MGS data that made this analysis possible, and the MGS spacecraft and mission operations team at the Jet Propulsion Laboratory and Lockheed Martin Astronautics for their contributions. We also thank the MOLA engineering and science support team, and Greg Neumann for his superior data preparation and analysis. We gratefully acknowledge the assistance of Stephen Pratt in the preparation of figures and Mikhail Kreslavsky for discussions. We thank Jim Zimbelman and an anonymous reviewer for their helpful comments and suggestions.

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